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The Influence of Water and Nitrogen on Growth and Development of Fodder Beet (*Beta Vulgaris*)

A dissertation

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Abstract of a dissertation submitted in partial fulfilment of the requirement for the Degree of Bachelor of Agricultural Science with Honours

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By

William Burrows

Fodder beet (*Beta vulgaris L. subsp. vulgaris var. Alba*) is commonly grown in New Zealand as a forage crop to feed dairy cattle. It has high potential yields and feed quality advantage over other traditional winter crops *e.g*. kale (*Brassica oleracea*) and swedes (*Brassica napobrassica*). For these reasons, farmers, agronomists, crop modelers and breeders have heightened their interest in this crop. However there has been increased concern about how nutrients and water are used to meet potential yield expectations in New Zealand. The rationale of this research is that different rates nitrogen and water availability will lead to differences in crop growth and development in the field and potentially final crop yield. The hypothesis is that if water and nitrogen are important sources of crop yield variation, they must influence yield components that include, cumulative radiation interception by the crop (R_{cum}), radiation use efficiency (RUE) and fraction of total dry matter partitioned in the root (f_{root}). A field experiment was conducted at Plant and Food Research Ltd at Lincoln, Canterbury, New Zealand, to investigate the influence of water and nitrogen on fodder beet growth and development and quantify their impact on yield. There were three nitrogen (0, 30 and 300 N ha^{-1}) and two water (zero and at field capacity) treatments.

Water was the main factor limiting crop yield as there was 98% higher dry matter in the irrigated treatment (28.31 t ha^{-1} DM) compared with the dry treatment (14.31 t ha^{-1} DM). Overall, 55% of this yield difference was explained by greater cumulative radiation interception. The irrigated treatment increased RUE by 27% (1.47 g DM MJ^{-1}) compared

with dry treatment (1.16 g DM MJ^{-1}). The fraction of total dry matter partitioned in the root (f_{root}) was 5.4% greater in the dry treatment (85.0%) compared with the irrigated treatment (79.6%). The 300 N dry treatment increased total dry matter production by 25% compared with the control nitrogen treatment (0 N). This was mostly explained by 42% greater radiation interception and 1.2% higher f_{root}. The irrigated 50 N and 300 N nitrogen treatments, increased dry matter production by 18% and 23%, respectively, compared with the control treatment. The yield increase from the N treatments was also explained by the larger amount of radiation intercepted by the crop at the end of the season. This was 14% and 42% higher for the 50 N and 300 N treatments, respectively, compared with the control treatment. F_{root} decreased by 8.3% in 300 N compared with the control, but 50 N had no effect. There was no significant difference in yield between the 50 N and 300 N treatments. A possible reason for this is that 300 N had reached 95% maximum yield 9 DAP or 102 ^{o}Cd before 50 N. After this point, light intercepted did not result in net photosynthesis and growth ceased earlier. Leaf chlorophyll concentration was 30% higher in water stressed plants. The dry 300 N and irrigated 300 N increased leaf chlorophyll by 10.3% and 13.8%, respectively, compared with the control. Greater leaf chlorophyll concentration did not seem to benefit total yield, as RUE was unaffected by nitrogen and decreased under water stress.

The results confirm the importance of nitrogen and water availability for crop radiation interception and consequently yield. In addition, RUE was significantly lower under limiting water availability. F_{root} was lower in both limiting water and nitrogen conditions whilst under irrigation. F_{root} increased under dry conditions and high rates of N. These findings can be used to develop a fodder beet simulation in model to optimize crop yield, nitrogen and water use. These results could also influence the priority of traits selected for during the plant breeding process of new cultivars with the aim of improving yield.

Keywords: *Beta Vulgaris*, canopy ground cover, chlorophyll, fodder beet, nitrogen, radiation interception, radiation use efficiency, water stress.

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1 INTRODUCTION

Fodder beet (*Beta vulgaris L. subsp. vulgaris var. alba*) is a member of the Chenopodiaceae family. It is a forage crop commonly grown in New Zealand to feed dairy cattle. This crop has gained popularity in this country due to very high potential yields, (19 to 35 tonnes of dry matter (DM ha^{-1}) (Chakwizira *et al.*, 2013b). Also due to its feed quality (12 MJ ME kg DM^{-1}) (Gibbs and Saldias, 2014) advantage over other traditional winter crops (*e.g.*) kale (*Brassica oleracea*) and swedes (*Brassica napobrassica*). There has been a major increase in fodder beet grown with an estimated 16,000 ha grown in New Zealand in the 2014-2015 season compared with an estimated 100 grown ha in 2006 (Gibbs and Saldias, 2014).

However there has been increased concern about how nutrients and water are used to meet potential yield expectations in New Zealand. Crop yield variation is attributed to water and nitrogen availability (White and Hodgson, 1999). Many crop models (*e.g.* Agricultural Production Systems Simulator; APSIMX) are able to predict crop yield based on these variables. Modelling the effect of water and nitrogen on the fodder beet yields can be a first approach to optimize crop yield, nitrogen and water use. These models facilitate farm decisions and agronomic management, such as optimum planting date, best choice of cultivars, evaluate weather risk and investment decisions.

For this experiment there are three nitrogen (0, 30 and 300 N ha^{-1}) and two water (zero and at field capacity) regimes (treatments) in fodder beet crops grown in the field. The rational is that different nitrogen and irrigation regimes will lead to differences in crop growth and development in the field and potentially final yield. By quantifying these differences, the optimum inputs of water and nitrogen could be further evaluated. The identification of plant characteristics that are the large contributors of yield can influence the priority of traits selected for in the plant breeding programs, with the aim of improving yield.

1.1 Aim and objectives

The aim of this experiment is to investigate the influence of water and nitrogen on fodder beet growth and development and quantify their impact on yield.

The first objective of this experiment is to investigate the impact of different water and nitrogen regimes on the patterns of canopy development for radiation interception and radiation use efficiency of fodder beet crops. The first step to achieve this objective is to determine how the crop responds to different amounts of nitrogen and water. The second objective is to assess the effects of water and nitrogen treatments on fodder beet leaf chlorophyll concentration.

2 REVIEW OF THE LITERATURE

2.1 Introduction

Fodder beet has become increasingly prominent in New Zealand as a forage crop to feed dairy cattle, mainly due to high yields. The environmental conditions the crop is grown in largely dictate how the crop performs. Reportedly crop yield variation is often caused by water and nitrogen availability (White and Hodgson, 1999). Specifically crop growth and yields have been attributed to the duration of the growth cycle which is highly dependent on climate, crop management and cultivar (Kooman *et al.*, 1996). Therefore, when crop management is at optimum, the differences in crop yield can be described by differences in total radiation intercepted by the crop. Radiation use efficiency is important as it determines how effectively the plant utilises light (radiation).

Canopy development processes determine how much of the incoming light is intercepted by the crop canopy. These components include leaf area index (LAI, leaf surface per unit soil surface), leaf area duration and the canopy extinction co efficient (k). Emergence, leaf appearance and leaf extension are all processes that influence these components. Limited water and nitrogen availability negatively affects canopy development, consequently radiation interception and radiation use efficiency.

The aim of this literature review is to explain and quantify factors that influence crop yield variation in fodder beet. The main topics reviewed are the components of yield (radiation interception, radiation use efficiency and sink strength) and their response to environmental factors (mainly temperature). Crop canopy growth and development processes, which include including crop emergence, leaf appearance, leaf extension, leaf duration and overall crop canopy growth. The response of all of these processes to water and nitrogen is investigated.

2.2 Nitrogen

In plants nitrogen is an essential element. It is required for DNA, RNA, protein (which are the basic components of enzymes), chlorophyll, ATP, auxins and cytokinins (Andrews *et al.*, 2013). Nitrogen is a major component in chlorophyll, a molecule that absorbs sunlight

to synthesise carbohydrates from water and carbon dioxide (Taiz and Zeiger, 2010). Higher amounts of nitrogen lead to greater production of chlorophyll in the chloroplasts. As a result of that, the rate of photosynthesis increases and this leads to an increase in plant growth. The main purpose of nitrogen is to stimulate the production of foliage canopy to allow for radiation interception especially for the plant straight after sowing. Malnou *et al.* (2006) found that 100 kg N ha^{-1} was needed to reach 85% canopy cover in sugar beet. Similarly Jaggard *et al.* (2009b) found an optimum economical rate of N fertiliser (considering fertiliser and seed price) of 100 kg N ha^{-1} to 110 kg N ha^{-1}.

2.3 Water

Water is a crucial component in plants. The total water content of pasture and crop plants are usually around 70-90% and 15-20% in seeds. Various functions of water in plants include maintaining cell turgidity for structure and growth; transporting nutrients and organic compounds throughout the plant and use in many reactions including photosynthesis. Water is also largely used for daily transpiration which is the process of water moving from the roots, through the plant and into the atmosphere (White and Hodgson, 1999). Low water availability is a major cause of crop yield reduction and is a severe environmental stress affecting agricultural production and quality (Boyer, 1982). In sugar beet, crops grown under irrigation had 21.8% higher dry matter (27.3 t ha^{-1}) than rain fed crops (22.4 t ha^{-1}) (Jaggard *et al.*, 2009a).

2.4 Components of crop yield

Crop growth and yields are related to crop duration which is dependent on crop management, cultivar and climate (Kooman *et al.*, 1996). If crop management is kept at an optimum level, the differences in yield can be expressed by the amount of radiation intercepted by the crop. According to Monteith and Moss (1977) the efficiency of crop production is defined as ratio of energy output to energy input (the amount of solar radiation intercepted to dry matter production produced by the crop). The differences between treatments in accumulated radiation interception and Radiation Use Efficiency (RUE) can therefore explain the variation in crop yield.

An equation by Jamieson *et al.* (2004) and Oliveira *et al.* (2016) conveys dry matter yield in Equation 1.

Equation 1: $\boldsymbol{Yield = \int_{em}^{t}(R_o \times R/R_o \times RUE) \times HI}$

Yield refers to yield, R_o is the total daily incident radiation received, R/R_0 is the amount of daily radiation intercepted by the plants canopy, represented as a fraction (or the fraction of the total daily radiation that is intercepted by the canopy). RUE is the radiation use efficiency of the crop, the efficiency of converting radiant to chemical potential energy. HI is the harvest index which is the amount of harvestable dry matter produced. In this research, HI will be referred to as the fractional percentage of dry matter in the root (f_{root}). HI as previously described is not appropriate to describe fodder beet as the entire plant biomass, not just the root is being used to feed animals. The sum of all of these factors over time (t) from the point of emergence (em) then equals the total amount of biomass accumulation.

2.5 Crop growth and development

Growth is an irreversible increase in plant dry matter as a result of the function of radiation interception and photosynthesis which lead to assimilate partitioning. Development is an irreversible change in the state of an organism. It is separate from growth but is driven by factors affecting growth (Hay and Porter, 2006). It is a fixed pattern or sequential and reversion is rare. For example leaf appearance, anthesis and pod fill. Development can proceed without growth. During the process of germination, for example seeds consume stored energy in order to generate new organs. The rate of developmental process is determined by temperature unless the plant is exposed to environmental stresses such as nutrient deficiency or drought (Goldberg, 1988). Other developmental processes include germination, initiation of flowering, duration of flowering, stem and stolon elongation.

2.6 Radiation

Radiation is energy from the sun and is usually expressed as a flux of energy per unit area of horizontal ground (Monteith and Moss, 1977). Radiation or irradiance is received by a surface per unit area and is measured in MJ per square metre (MJ m^{-2}). Photosynthetically active radiation (PAR) is the spectral range of solar radiation from 400 nm to 700 nm that photosynthetic organisms *e.g.* plants, use in the process of photosynthesis. Approximately 50% of the radiant energy reaching the earth's surface is PAR, which means only half the radiant energy is useful for plant growth (Taiz and Zeiger, 2010). According to Monteith (1972), the maximum amount of dry matter accumulated by the crop is strongly correlated to the amount of solar radiation intercepted during growth.

2.7 Radiation use efficiency

Radiation use efficiency (RUE; g MJ^{-1}) is a measurement relating to dry matter production (g m^{-2}) in proportion to the amount of PAR energy (MJ m^{-2}) that is intercepted and accumulated over the growing period. Sinclair and Muchow (1999) found that increasing maximum leaf photosynthetic rate resulted in increased RUE and this rate differs between various crop species. Hoffmann and Kluge-Severin (2010) found that the RUE of both autumn and spring sown sugar beet produced 1.2 g DM per MJ solar radiation. An equation from Hoffmann and Kluge-Severin (2010) as shown in Equation 2 described RUE as:

Equation 2: $$\boldsymbol{RUE} = \sum_{\boldsymbol{sowing}}^{\boldsymbol{harvest}} \frac{\boldsymbol{DM}}{\boldsymbol{radiation\ interception}}$$

RUE is determined by relating total dry matter (DM) to the accumulated radiation intercepted over the growing period. It has been found that crop primary production is linearly related to PAR interception (Monteith, 1972). The slope of this relationship is the RUE. Hoffmann and Kluge-Severin (2010) fitted a linear regression of this type for various locations, sowing and harvest dates in a study done for of sugar beet. The equations, y=1.2 x -7.2 and y=1.1 x+ 174 represents the RUE of both autumn and spring sown sugar beet which produced 1.2 g and 1.1 g DM per MJ solar radiation, respectively. As reported

by Monteith and Moss (1977), greater intercepted radiation means greater total dry matter yield and RUE is also species dependant.

2.8 Factors driving yield: Temperature, Thermal time, Base temperature

Temperature is the main driver of yield, given adequate nutrition, moisture, and efficient weed, pest and disease control. Temperature affects the rate of plant growth and development. The rate of plant processes such as respiration, photosynthesis and nutrient uptake are also dependant on temperature. It can also determine the switch between one development phase to another (White and Hodgson, 1999).

Responses to temperature can be quantified by base, optimum and maximum temperatures (cardinal temperatures). Base temperature is the lowest temperature that physiological processes start which lead to an increase in biomass and further stages in development. The optimum temperature is when the rate of a process is at the highest observed. Maximum temperature is the point where physiological processes stop (Porter and Gawith, 1999). For red beet (*Beta vulgaris*), McCormick *et al.* (2014) found that the base temperature was 4.2 °C, optimum temperature was 35.9 °C and maximum temperature was 44.4 °C. For fodder beet Chakwizira *et al.* (2016) found the base temperature was 0 °C. Temperature has a major influence on leaf appearance, leaf expansion, tiller and root extension. Repkova *et al.* (2009) reported that air temperature affected leaf appearance, mainly at the start of the growing season and there is a positive correlation between leaf expansion rate and soil/ air temperature. Cardinal temperatures are often used to predict crop production. One way of determining this is by using thermal time (Tt) or growing degree days. The simplest way of quantifying thermal time as described by White and Hodgson (1999) in Equation 3 and Equation 4 is:

Equation 3: $\boldsymbol{Thermal\ time(TT)} = \sum(\boldsymbol{T_{mean}} - \boldsymbol{T_{base}})$

Equation 4: $\boldsymbol{T_{mean}} = \frac{\boldsymbol{Maximum\ temperatre + Minimum\ temperature}}{\mathbf{2}}$

The temperature mean is found by adding the maximum and minimum temperature then dividing by 2 (Equation 4). Thermal time is then calculated by subtracting the base temperature mean from the mean temperature (Equation 3). This calculation can be done weekly and, or daily. However this equation has limitations as the rate of development in most plant species is not linearly related. It is not suitable for a temperate climate as the temperature significantly changes throughout the day. Day length affects on development are not accounted for (Hodges, 1991).

2.9 Canopy Components

The characteristics of the leaf canopy are important for the interception of light. Light as described earlier drives yield. Components that are important to canopy formation are leaf area index (LAI, leaf surface per unit soil surface), leaf area duration and the canopy extinction co efficient (k). LAI is the most important factor that determines the amount of radiation that is intercepted. LAI at which 95% of radiation that is intercepted is called critical leaf area index. As reported by Chakwizira *et al.* (2016), fodder beet reached a maximum LAI at 95%. At this point leaves have expanded to the maximum size; therefore maximum radiation interception has been reached. Chakwizira *et al.* (2016) reported that the critical LAI for fodder beet (*Beta vulagris subsp. Vulgariss var.alba L.)* was 3-4 m^2 m^{-2}. Leaf area duration is the lifespan of the leaves and will affect the total radiation that is intercepted over the life of the crop.

2.10 Leaf appearance

Leaf appearance determines the rate at which a plant obtains maximum LAI. Temperature is the main environmental factor that drives leaf appearance rate. Milford *et al.* (1985) reported that leaf appearance was a linear function of thermal time, in sugar beet (*Beta vulgaris*) accumulation of temperature started above 1 °C and leaf expansion rate responded above 3 °C.

2.11 Leaf expansion

Leaf expansion determines leaf size therefore maximum leaf area of the plant for radiation interception. After initiation, the developing leaf enters a stage of growth where it is dominated by two different processes of cell division and cell expansion (Hay

and Walker, 1989). Firstly, cell division involves the production of new cell material. Secondly, cell expansion is driven by turgor pressure within the cell, greater pressure means more water within the cell which drives cell growth (Dale, 1988). The maximum leaf size that can be reached is genetically determined however this is highly dependent on environmental factors such as temperature, water, radiation and nitrogen (Hay and Walker, 1989). These environmental factors affect the daily leaf expansion rate (m^2 leaf day^{-1}). Leaf area expansion rate (LAER) is significantly reduced by mild water deficits that would normally not affect photosynthesis. Rates of leaf expansion and cell division are linearly related to leaf temperature (Tardieu *et al.*, 1999). In fodder beet, Chakwizira *et al.* (2016) found that the LAER in unconstrained water and N supply was 0.0025 m^2 m^2 $^oCd^{-1}$ and 0.0034 m^2 m^2 $^oCd^{-1}$. Limited water supply reduced LAER by 32% and 26%. At later stages of growth, plants that were limited by nitrogen had a reduction of 50% from 0.0024 m^2 m^2 $^oCd^{-1}$ for 200 kg N ha^{-1} to 0.0012 m^2 m^2 $^oCd^{-1}$ in no N.

2.12 Leaf area duration

Leaf area duration is the ability of the plant to maintain green leaf area over the crop duration. It is the amount of time the leaf contributes to photosynthesis (Basra, 1994). Once the leaf reaches its maximum size it becomes an asset to the plant as it will intercept light and will contribute to the supply of carbon (BuchananWollaston, 1997). Nitrogen supply has a significant influence on leaf area duration. Vos and Biemond (1992) reported that elevated nitrogen supply increased the life span of the 12^{th}, 13^{th} and 14^{th} leaves by 80 to 100 days. It is to be noted that in fodder beet, growth is indeterminate which means the plant will continue to produce leaves during its crop duration. This is different from determinate growth, where the plant will stop growth after a genetically pre determined organ or structure (*e.g* flower) has been fully formed (Hay and Walker, 1989). For example pasture and temperate cereals follow this life cycle. As reported by Watson (1947), sugar beet has a longer growing season and leaf area duration compared to cereals and potatoes. Sugar beet had a very long leaf area duration of 33 weeks compared to 21 weeks for potatoes, 25 weeks for wheat and 17 weeks for barley. This resulted in higher dry matter yields for fodder beet (12 t ha^{-1}) compared with wheat (9.5 t ha^{-1}), potatoes (7.7 t ha^{-1}) and barley, (7.3 t ha^{-1}) due to high leaf area index and long leaf duration.

2.13 Water stress

Crop growth and yield are severely restricted by water stress. Cell expansion is highly sensitive to water deficit as turgor pressure is reduced when water is scarce (Farooq *et al.*, 2009). When plant cells experience a water deficit, cellular dehydration occurs which means that the turgor pressure within a cell decreases. Turgor pressure equals positive hydrostatic pressure and by maintaining this pressure it will cause cell growth. When there is insufficient water inside the cell to maintain turgor it will become flaccid therefore growth ceases. Sinclair (1983) found that when plants were exposed to periods of drought, zero turgor was reached after small changes in relative water content. As a result of a loss of turgor, leaf and cell expansion rate will decrease to minimise water losses from transpiration (Dale, 1988). As shown in Figure 1 leaf expansion is completely repressed under a slight decrease in water potential. As water potential decreases, photosynthesis decreases, due to water stress.

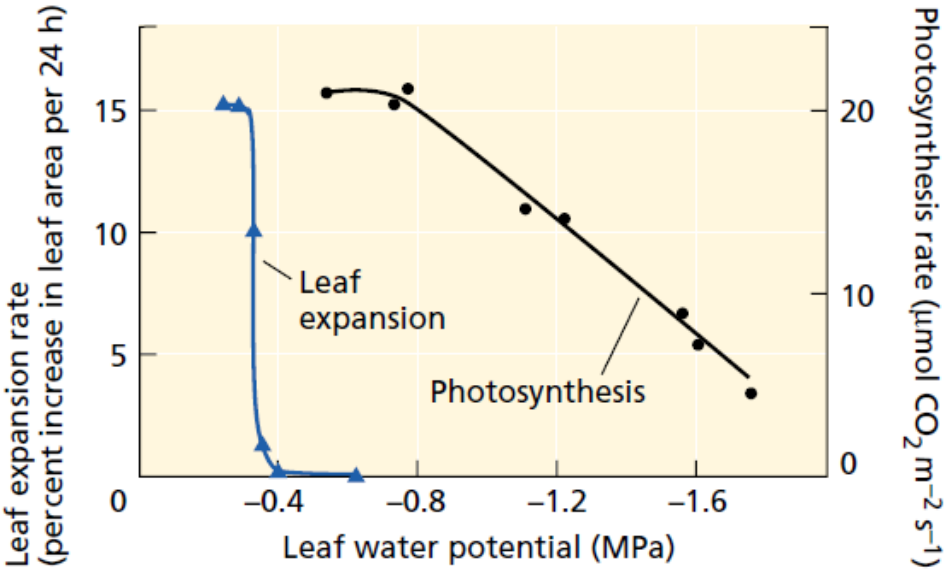

Figure 1: Effects of water stress on photosynthesis and leaf expansion of sunflower (*Heliantus annus*) (Taiz and Zeiger, 2010).

2.14 Nitrogen stress

Plant nitrogen availability has a large influence on the rate of leaf expansion and final leaf size of all crops. Morton and Watson (1948) found that in sugar beet, plants receiving high nitrogen supply had more and larger cells compared with leaves of low nitrogen

supply. This shows that nitrogen supply affects both cell division and cell extension of the leaf. Trapani *et al.* (1999) showed that nitrogen supply had a large impact on leaf size. Reduced N supply (21 ppm) in fully expanded leaves led to a reduced number of cells per leaf, reduced leaf area per cell and cell area was significantly reduced. Roggatz *et al.* (1999) showed that the stage of development when nitrogen stress is applied has a large effect on final leaf size. N stress at earlier stages of leaf development when cell division is occurring resulted in a greater decrease in final leaf size of 80%. Also in this same study low N supply resulted in lower individual leaf dry matter.

2.14.1 **Nitrogen with contrasting water availability**

Water supply is a critical factor for the effective use of nitrogen application. Nitrogen and water stress has a large impact on canopy development of fodder beet. Chakwizira *et al.* (2016) found that fodder beet plants that received neither N nor irrigation did not reach the range of LAI_{crit} during the growing season. Fodder beet that was rain fed took to mid February to reach LAI crit, which was one month longer than the irrigated crop, where it reached LAI crit in mid January. A low supply of nitrogen means that the plant cannot produce the potential number of leaves per plant, reach the potential area per leaf or maintain the nitrogen concentration in leaves and other organs necessary for unrestricted growth (Greenwood *et al.*, 1990). Due to short supply of nitrogen under stressful conditions plants may focus on the maintenance of leaf size at a cost of decreased photosynthesis per unit leaf area, or maximise productivity per unit leaf area at a cost of maximum leaf size (Vos and van der Putten, 1998). A larger supply of nitrogen enhances apical branching in some crops. This means more leaves are formed per plant therefore LAI is greater. The timing of developmental events are not affected by N supply, such as rate of leaf appearance (Vos and Biemond, 1992).

It was found that in kale (*Brassica oleracea)*, water use efficiency increased with greater N supply from 35.3 kg DM ha mm^{-1} for treatments receiving less than 30 kg N ha^{-1} to 40.6 kg DM ha mm^{-1} for treatments receiving greater than 120 kg N ha^{-1}. Total N uptake increased from 180 kg N ha^{-1} under summer drought treatments to 220 kg N ha^{-1} for fully irrigated. Water use doubled when kale was fully irrigated compared with summer drought conditions. This led to 76.3% greater dry matter yield in the irrigated compared

with the drought regime (Chakwizira *et al.*, 2013a). This suggests that water availability increases the ability to utilise either fertiliser N and, or mineral N which leads to large increases in growth.

2.15 Effect of water availability on RUE

Water stress has been shown to decrease Radiation Use Efficiency (RUE) in both C3 and C4 species (Jamieson *et al.*, 1995a). This is because water deficits negatively influence the maintenance of cell turgidity for structure and growth (White and Hodgson, 1999). Water deficits also influence reactions including leaf photosynthesis rates which primarily cause stomata closure and under severe water deficits increases mesophyll resistance to CO_2 diffusion (Gastal and Durand, 2000). Jamieson *et al.* (1995a) reported that RUE declined linearly with water deficit; however this trend was also dependant on timing and duration of the deficit. In an experiment involving the effect of drought on sugar beet, it was found that drought reduced RUE from 1.64 g DM MJ^{-1} for fully irrigated crops to 1.37 g DM MJ^{-1} and 1.51 g DM MJ^{-1} for early and late drought treated crops, respectively (Brown *et al.*, 1987). As a result of that, dry matter yield decreased from 21 t ha^{-1} for fully irrigated crops to 16.1 t ha^{-1} and 17.9 t ha^{-1} for the early and late drought crops, respectively. The RUE decrease was greater with drought stress at early plant development stages compared with the late crop stages. This shows that water is highly important for the growth and development of the plant especially during emergence, canopy development and leaf extension stages. As explained in Section 2.11, water availability has a large influence on leaf extension and expansion, which in turn affects RUE. As reported by Jaggard *et al.* (2009a), in sugar beet, in 1982 and 2006, RUE decreased from 1.46 g DM MJ^{-1} in irrigated to 1.26 g DM MJ^{-1} in rain fed crops in 1982. Similarly in 2006 RUE decreased with 1.37 g DM MJ^{-1} in irrigated and 1.22 g DM MJ^{-1} in rain fed crops.

2.16 Sink strength

With the aim of improving crop yield, there have been two key areas of research. 1) Increasing carbohydrate production in the leaves (increasing source capacity). 2) improving the utilisation of photoassimilates by sink organs (enhancing sink strength) (Bihmidine *et al.*, 2013). Sink organs essentially demand photosynthetic assimilates for it

to be used in growth, respiration and storage compounds. All parts of the plant at some point in development become sinks. Sink strength is the competitive ability of a sink organ to import photoassimialtes. This depends on the physical size and physiological capability of the organ (Ho, 1988). In the case of fodder beet the root is the biggest sink organ and competes with the foliage for assimilates. Actual sink strength is affected by the availability of assimilate supply, how close the sink is to the source and most importantly the ability of the sink to receive or attract assimilate. This ability to attain assimilate is called the potential sink strength which is genetically determined and can be reached when under optimal environmental conditions (Ho, 1988).

2.17 Conclusion

In conclusion yield differences due to environmental stresses can be explained by various levels of radiation intercepted by the canopy, radiation use efficiency and fraction of total dry matter partitioned in the root. Radiation interception is dependent on canopy components including leaf area index and leaf area duration. Water stress and low nitrogen availability greatly limit leaf expansion, which leads to a decrease in canopy cover and consequently a decrease in the interception of light by the canopy. Canopy duration is greatly influenced by nitrogen availability. This affects the amount of time the leaves contribute to photosynthesis. Greater water availability increases uptake of mineral N out of the soil and uptake of water by the plant. Water stress negatively influences radiation use efficiency. The sink strength is the competitive ability of a sink organ to import photoassimilimates, which depends on the physical size and physiological capability of the organ. Sink strength may further explain differences in the partitioning pattern of crops.

This study will quantify yield differences by measuring these yield components under various water and nitrogen treatments in fodder beet.

3 MATERIALS AND METHODS

3.1 Cultivar

The cultivar of fodder beet (*Beta vulgaris L. subsp. vulgaris var. alba*) used in this experiment was 'Ravage.' This is a modern cultivar, that has been released in New Zealand in 2014/2015. Roots are uniform in size with moderately high potential yields ranging from ~18 to 30+ t DM ha^{-1}. It is a high dry matter type (18-21%), with high resistance to bolting (Agricom, 2015).

3.2 Experimental site

The trial was conducted at Plant and Food Research Ltd rain shelter facility at Lincoln, Canterbury, New Zealand (43° 38'S, 172° 30'E). The experimental site is shown in (Plate 1). The soil at the site is a Templeton silt loam over sand (Typic Immature Pallic soil). The deep (>1.6m) Templeton silt loam is moderately well drained with a plant available water holding capacity of approximately 190 mm m^{-1} of depth (Jamieson *et al.*, 1995b). This site allows for complete removal of rainfall from the entire experimental site, therefore enabling soil water availability to be controlled by the different water treatments (Martin *et al.*, 1990). The rain shelter is a durolite greenhouse, 54 m long by 12 m wide mounted on wheels which run along parallel rails 12 m apart and 216 m long (Plate 2). The area between the rails is divided into four blocks, each of the blocks is rotated into an experiment every four years. When the rain shelter is not covering the experiment it is parked 54 m away so wind and shade effects are avoided. There are four rain sensors located on the roof of the motor shed which activates the winch when three of them are wet. The rain shelter then moves across onto the site in less than three minutes. The rain sensors are heated to prevent activation from dew. There is a delay of 30 min from when it stops raining to when the rain shelter moves off the experiment.

Plate 1 : Image of rain shelter experimental taken on the 23rd December 2016 at Lincoln, Canterbury, New Zealand, 2016-2017.

Plate 2: Image of rain shelter over experimental site, taken 17th May 2017 at final harvest at Lincoln, Canterbury, New Zealand, 2016-2017.

3.3 Meteorological data

The long term average annual rainfall in this area is 603 mm, monthly rainfall is lowest in February with 37 mm and highest in May with 67 mm (Table 1). Evapotranspiration is at its highest in December with 144 mm and lowest at 18 mm in June. The maximum (~22^{o}C), mean (~17 ^{o}C) and minimum temperature (~12^{o}C) are highest in the summer months of January and February and lowest in the winter months of June and July. Daily average solar radiation is highest in December with 22.8 MJ M^{-2} and lowest in June with 4.6 MJ M^{-2}. Meteorological data were sourced from Lincoln Broadfield meteorological station situated approximately 200 m south east from the experimental site (43° 37'S, 172° 28'E) (Table 1).

Table 1: Climate data (2000-2016) for rainfall, Penman total potential evapotranspiration (E_{po}), daily maximum (T_{max}, mean (T_{min}) and minimum (T_{mean}) average temperature, wind run and mean daily solar radiation recorded at Broadfields Meteorological Station.

Month	Rainfall (mm)	E_{po} (mm)	T_{max} (^{o}Cd^{-1})	T_{mean} (^{o}Cd^{-1})	T_{min} (^{o}Cd^{-1})	Wind Run (km d^{-1})	Solar Radiation (MJ M^{-2} day^{-1})
Jan	42	141	21.7	16.6	11.5	393	22.1
Feb	37	110	21.6	16.7	11.8	383	19.2
Mar	43	89	20.2	15.0	9.9	369.0	14.8
Apr	56	46	17.3	12.4	7.5	320.0	9.4
May	67	28	14.7	9.9	5.1	321.0	5.9
Jun	63	18	12.1	7.1	2.2	301.0	4.6
Jul	45	20	11.3	6.4	1.4	291.0	5.4
Aug	62	36	12.5	7.8	3.1	328.0	8.2
Sep	35	62	15.1	10.0	4.9	367.0	12.5
Oct	54	98	16.6	11.4	6.2	387.0	17.8
Nov	47	127	18.5	13.3	8.0	394.0	22.3
Dec	51	144	20.2	15.6	10.7	405.0	22.8
Annual	603	919	16.9	11.8	6.9	355	13.8

3.4 Management

3.4.1 Planting and planting preparation

Prior to the fodder beet, 'Milton' oats (*Avena sativa L.*) were drilled on the 20th April 2016 at 110 kg ha^{-1} in order to take up nitrogen left in the soil over winter. A basic soil test was done for the site on the 6th May 2016. The results are shown in Table 2. On the 23rd August 2016, the oat crop was removed using a Cibus forage harvester. On the 5th

September 2016 the site was ploughed and cambridge rolled on the 6th September 2016. Soil samples were taken on all plots to a depth of 180 cm to measure mineral nitrogen. Depths include 0-15,15-30,30-60,60-90,90-120,120-150 cm. On the 17th October 2016 the site was power harrowed. On the 18th October 2016 200 kg ha^{-1} of KCL, 250 kg ha^{-1} triple superphosphate, 200 kg ha^{-1} NaCL and 30 kg ha^{-1} of Boronate 15% were applied to the trial site using chest spinners. Also on the 18th October, the site was Cambridge rolled and harrowed. 'Rivage' fodder beet (*Beta vulgaris L. subsp. vulgaris var. alba*) was sown at 110,000 plants ha^{-1} in 45 cm row spacings using a Stanhay 4 row air seeder on the 18th October 2016. The crop emerged for all plots on the 27th October 2016.

Table 2: Basic soil test results for experimental site in Lincoln, Canterbury, New Zealand. Ph, Olsen P (µg ml^{-1}), potassium, calcium, magnesium, sodium and sulphur were taken at a depth of 0-15 mm on the 6th May 2016.

Test	Result
Ph	6.2
Olsen P (µg mL^{-1})	22
Potassium (QTU)	9
Calcium (QTU)	11
Magnesium(QTU)	15
Sodium (QTU)	8
Sulphur (QTU)	4

3.4.2 **Weed, pest and disease control**

Many agrichemicals were used to control many weeds, pests and diseases. In order to control broad leaf and grass weeds clomazone (Magistar) and ethofumesate (Nortron) was applied. For the control of springtails pirimiphos-methyl + permethrin (Attack) was used which is a broad spectrum insecticide. Bentanal Quattro (Four active ingredients) is a herbicide which was used for the control of broad leaf weeds. For weed control post emergence metamitron (Goltix) and Phenmedipham + desmedipham (Bentanal Forte) was applied. Lambda-cyhalothrin and oxirane (Karate Zeon) were used to control foliar pests and cutworm, which is an insecticide. Downy mildew and powdery mildew were controlled with Copper oxychloride, which is a protectant fungicide. Leaf rust was controlled with two fungicides; Cyroconazole and trifloxystrobin (Escolta). Agrichemical information was sourced from Novachem (2016). Full details of different agrichemicals applied to fodder beet are shown in Appendix 1.

3.5 Physical environmental measurements

3.5.1 Soil moisture

Automated Time-Domain Reflectometers (TDR) from Campbell Scientific®, model CS 650 (Logan, Utah, USA) were used to determine soil moisture. The amount of irrigation application was calculated by using Equation 5.

Equation 5: $\boldsymbol{Irrigation = (TC - TDR) \times ID}$

TC is target capacity (80%), TDR is the average soils water content for the 12 irrigated plots and ID is the irrigation depth (1.8 m). TDR's were installed soon after emergence. Within each plot there are 8 TDR's recording soil water content every 15 minutes and were installed at the following depths: 0-150 mm in the row, 0-150 mm in between the row, 150-300 mm in the row, 300-600 mm in the row, 600-900 mm, 900-1200 mm, 1200-1500 mm and 1500- 1800 mm.

This allowed for soil water content to be accurately measured so the optimum amount of water could be applied to the irrigated plots to reach field capacity

3.5.2 Soil and air temperature and radiation

Soil temperature, air temperature and radiation data for the experimental duration were sourced from Broadfields Meteorological station at Lincoln, Canterbury, New Zealand. Mean monthly soil temperature ranged from 7 ^{o}C in May to 16.6 ^{o}C in January and February (Figure 2). Average daily total solar radiation ranged from 6.2 MJ m^{-2} in May to 22.8 MJ m^{-2} in January (Figure 3).

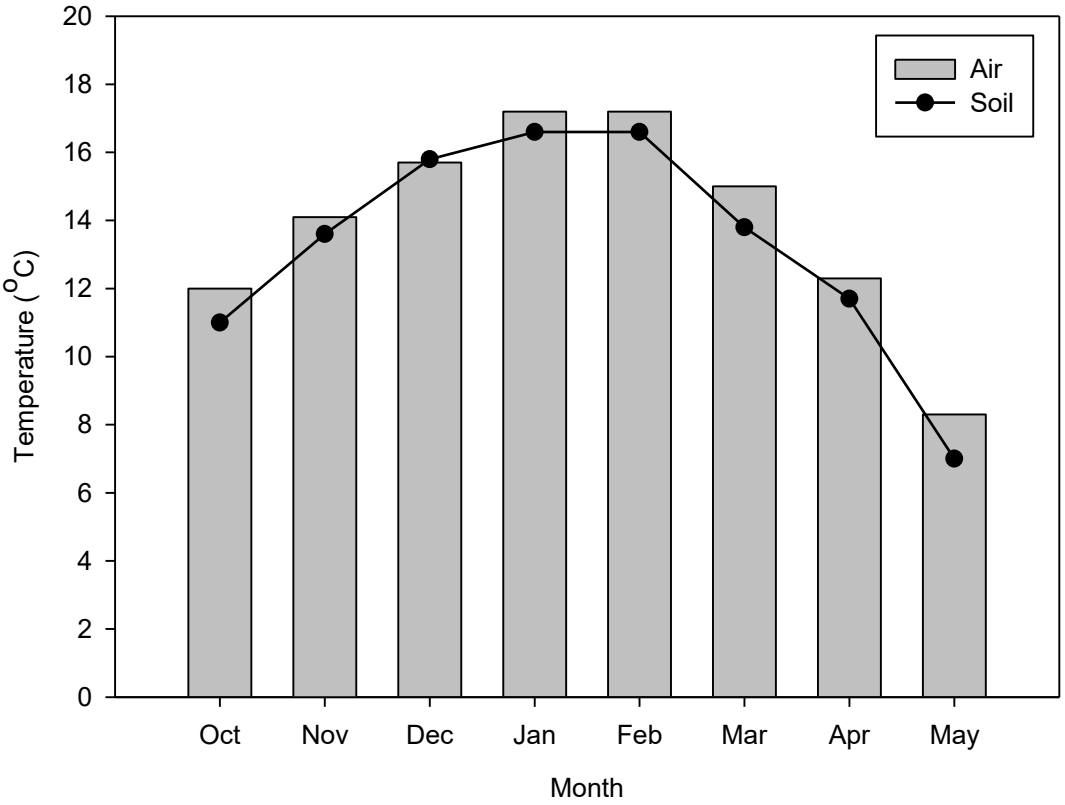

Figure 2 : Mean monthly air and soil temperature (°C) from planting to final harvest. Data was sourced from Broadfields Meteorological Station, Lincoln, New Zealand. Soil temperature was measured at 10 cm below soil surface.

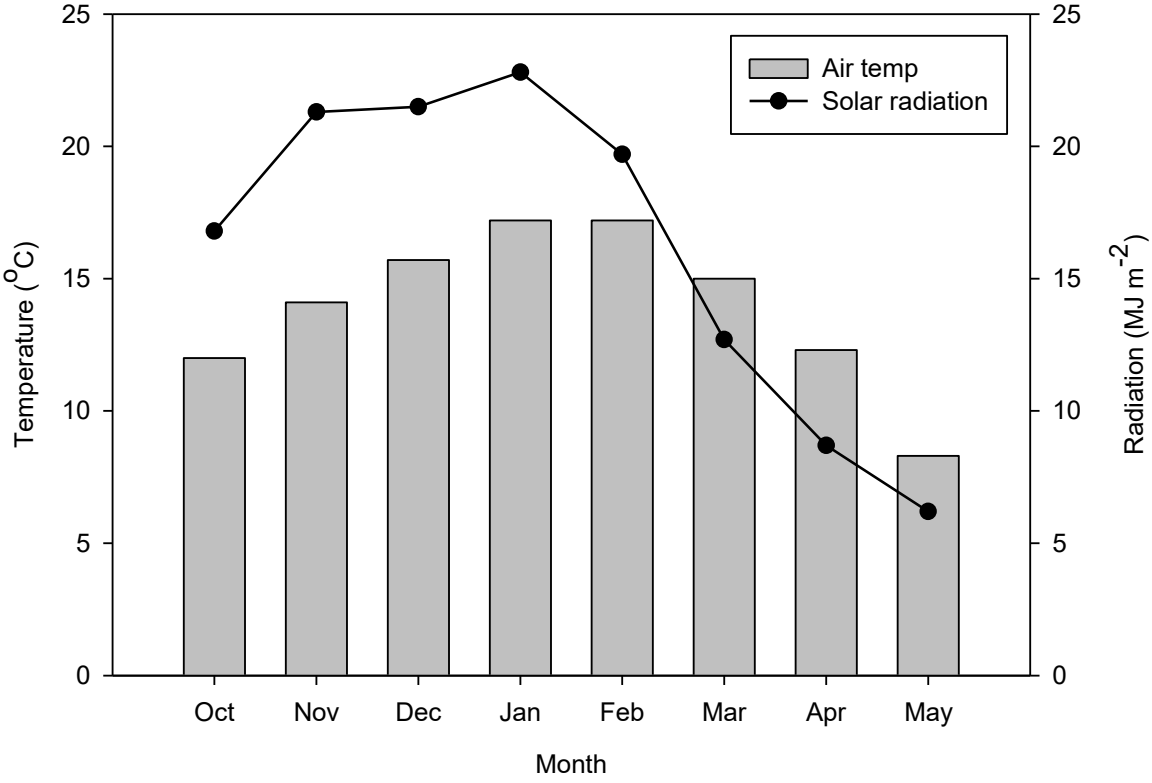

Figure 3: Mean monthly air temperature (°C) and mean monthly solar radiation (MJ m^{-2}) planting to final harvest. Data was sourced from Broadfields Meteorological Station, Lincoln, New Zealand.

3.6 Treatments

3.6.1 **Water**

There were two water treatments (dry and irrigated). An illustration of the full experimental site with labelled plots and treatments is shown in Figure 4. Water was applied to the irrigated plots via drip irrigation system. After sowing, two 5 ml applications were applied on the 25th and 28th of October 2016. During the crop duration, the amount of drip irrigation applied was determined by using Equation 5. This involved the average soil moisture from the 12 irrigated plots, target capacity of 80% and irrigation depth of 1.8 m. In the rain shelter, there was a plant available water holding capacity of 190 mm m^{-1} of depth. Water content was measured down to a depth of 1.8 m. 190 mm x 1.8 m depth =342 mm of water holding capacity down to 1.8 m. Target water content of the soil at the site is 80% of water holding capacity = 342 x 0.8 = 274 mm.

The experiments soil water content was refilled weekly to the irrigation target of 274 mm (down to 1.8 m). On the 23rd of November, the first application of the fully irrigated treatment (30 mm) was applied to the irrigated plots. This allowed for soil water content to be accurately measured so the optimum amount of water can then be applied to the irrigated plots to reach the target capacity. Water application dates and amounts are shown in Appendix 2.

3.6.2 **Nitrogen**

Three nitrogen treatments were applied in combination with two water treatments. This includes 0 kg N ha^{-1} (Control), 50 kg N ha^{-1} (50 N) and 300 kg N ha^{-1} (300 N) for both the irrigated and the dry treatment (Table 3). Nitrogen was applied in three split applications on the 28th October, 18th January and 15th February. Nitrogen was in the form of liquid urea (46% N) which was applied via the drip irrigation system with a small amount of water. For the first application, 50 N treatments got 25 kg N ha^{-1} and 300 N treatments got 100 kg N ha $^{-1}$. Urea was dissolved via mixing with 5 L of hot water. Before application 3 mm of water was applied to each of the treatments to wet up the soil. Liquid N was then applied in 2.1-2.5 mm. Additional water was applied to make up to 10 mm total for all plots including dry and 0 N plots. The second application was exactly the same as the first application; 50 N treatments got 25 kg N ha^{-1} and 300 N treatments got 100 kg N ha^{-1}.

The third application involved only a further 100 kg ha^{-1} to the 300 N treatments applied in 10 mm water. The 0 N and 50 N treatments also got 10 mm water. All nitrogen and water treatments are shown in Table 3.

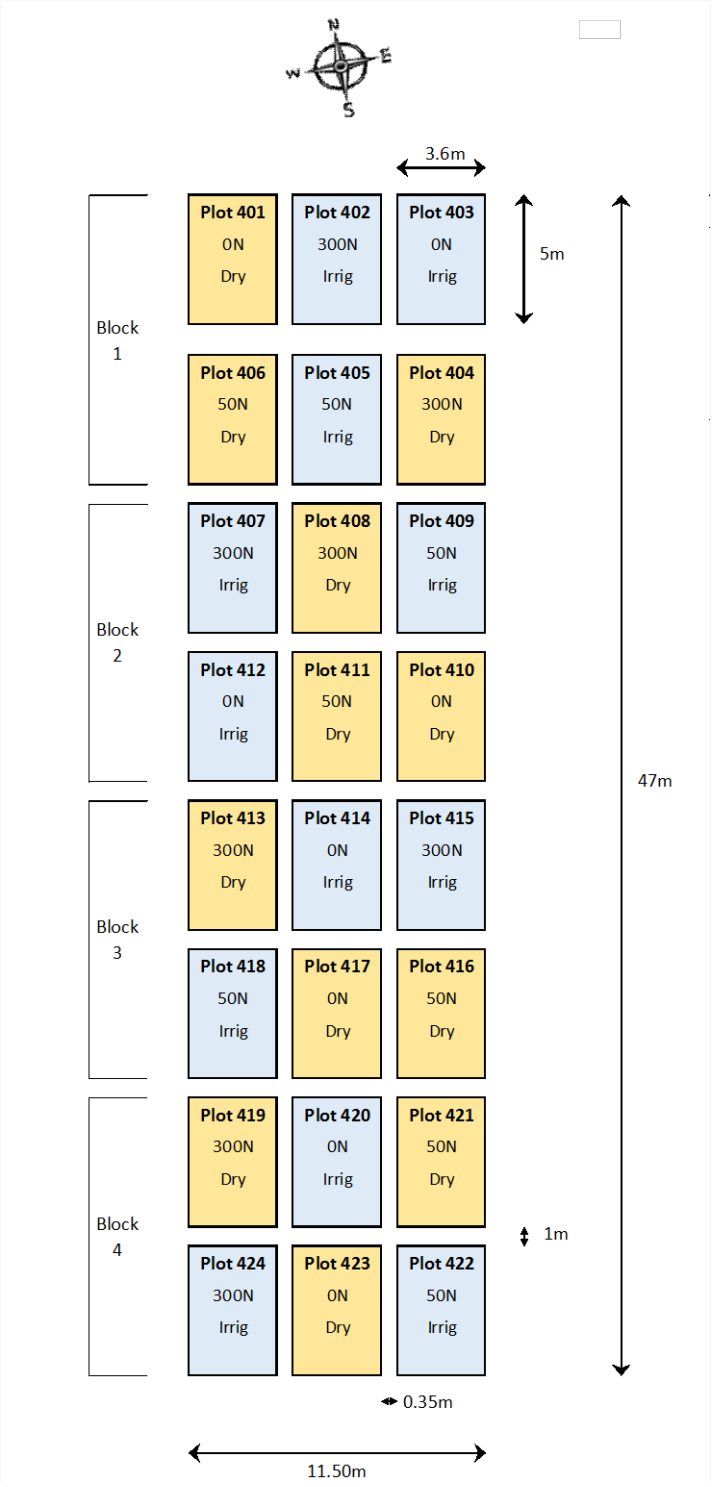

Figure 4: Diagram of plots and labelled treatments for the experiment, conducted at Lincoln, Canterbury, New Zealand in 2016-2017.

Table 3: Nitrogen and water treatments for the experimental site at Lincoln, Canterbury, New Zealand.

Treatment	Nitrogen	Irrigation
1	0	Dry
2	50	Dry
3	300	Dry
4	0	Full
5	50	Full
6	300	Full

3.7 Crop Measurements

3.7.1 Crop Biomass

A series of destructive harvests were taken on the 19th December 2016, 22nd February 2017, 22nd Match, 19th April and 17th May. This was done to obtain fodder beet biomass measurements. For the December harvest 0.45 m^2 was taken from each of the 24 plots to obtain fresh weight and number of plants (Plate 3). A 1 m fibre glass rod was laid between a row to determine harvestable area (Plate 4). For the February, March and April harvests 1 m^2 (two rows at 1 m) was taken for each of the plots. For the final harvest 2 m^2 (four rows at 1 m) was taken for each of the plots. For all harvests sub samples were taken of two middle weight roots from each plot. The roots from the sub sample were then washed and separated for root, petiole, leaf and dead organs. Fresh weight for each component was then weighed. Leaf for the 24 plots was then put through a leaf area machine (LI-Cor, LI-3100 area meter, -Li Cor, Inc. Lincoln, Nebraska, USA) to measure leaf area in m^2. Constituents were then put in the oven at 60 ^oC for two to three days to dry until constant weight is reached. Later the constituents were weighed again to determine dry weight.

Plate 3: Image of fresh weight measurement at trial site taken 17th May 2017 at final harvest.

Plate 4: Image of 1 m^2 quadrat, fibre glass rod is 1 m long, taken on the 17th May 2017 at final harvest at Lincoln, Canterbury, New Zealand.

3.7.2 **Green seeker**

A Trimble® Green seeker® crop sensing instrument (Trimbe, Agriculture Division, Colorado) was used to determine the normalised difference vegetation index (NDVI). NDVI is an index of plant "greenness" or the amount of photosynthetic activity. The index is based off the premise that different types of surfaces reflect different wavelengths of light. Vegetation that is photosynthetically active absorbs a large amount of red light (0.50 nm-0.70 nm) while reflecting large amounts of near infrared light (0.70 nm-0.90 nm). Vegetation that is dead or stressed reflects more red light and less near infrared light (Carlson and Ripley, 1997). NDVI is the near infrared band value for a cell, minus red band value for a cell, divided by near infrared band value plus red band value as shown in Equation 6.

Equation 6: $\boldsymbol{NDVI = \frac{(NIR-RED)}{(NIR+RED)}}$

Values of NDVI range from -1.0 to 1.0. Higher values mean a larger difference between the red and near infrared radiation which is associated with highly photosyntheically active radiation. However there are a large number of factors that can influence the strength of the NDVI value. These include vegetation moisture, soil moisture, atmospheric conditions, scale and imagery, vegetative cover, soil type and soil management. Light from the soil surface can influence the NDVI values significantly. In order to minimise variation due to the soil surface the NDVI can be scaled. Scaled NDVI (Equation 7) can be calculated as follows:

Equation 7: $\boldsymbol{Scaled\ NDVI = \frac{(NDVI-NDVIo)}{(NDVIs-NDVIo)}}$

$NDVI_o$ is the NDVI value for bare soil (LAI=0). $NDVI_s$ is a surface fractional vegetation cover of 100%. In this form, the scaled NDVI reduces the effect of soil reflectance and provides a more accurate representation of vegetation cover.

A series of 25 NDVI measurements were taken throughout the crop growing season using a Green seeker. Measurements were taken once per week over the duration of the

experiment. This amounted to 25 weeks of measurements on the following dates: 16th November 2016, 24th November 2016, 29th November 2016, 8th December 2016, 14th December 2016, 19th December 2016, 29th December 2016, 5th January 2017, 11th January 2017, 20th January 2017, 27th January 2017, 2nd February 2017, February 2017, 9th February 2017, 17th February 2017, 22nd February 2017, 3rd March 2017, 8th March 2017, 15th March 2017, 24th March 2017, 31st March 2017, 10th April 2017, 18th April 2017, 27th April 2017, 2nd May 2017 and 15th April 2017. Each measurement involved one Green seeker reading over each of the individual plots. One bare soil reading was taken every week so scaled NDVI could be calculated. The Green seeker was raised approximately 800 mm above the crop canopy and emitted visible red (660 nm) and near infrared (770 nm) wavelengths. The instrument recorded reflectance of these wavelengths at 10 readings per second and data was saved to a Trimble Nomad handheld computer. An average of 30 measurements was recorded over one fodder beet row in each plot. The same row was monitored over the duration of the experiment.

3.7.3 **Chlorophyll Meter**

The Apogee MC-100 chlorophyll meter (Apogee Instruments Inc, Logan, Utah, USA) was used to measure chlorophyll concentration index (CCI). This index is used in a generic model, to determine chlorophyll concentration in the leaves. The current model was calibrated using 22 species of crops, outlined in Parry *et al.* (2014). However this model has not been tested for fodder beet crops.

Weekly CCI measurements were taken during 22 weeks on the following dates: 25th November 2016, 8th December 2016, 23rd December 2016, 5th January, 11th January, 18th January 2017, 25th January 2017, 1st February 2017, 9th February 2017, 17th February 2017, 22nd February 2017, 2nd March 2017, 7th March 2017, 14th March 2017, 22nd March 2017, 31st March 2017, 6th April 2017, 13th April 2017, 21st April 2017, 27th April 2017, 3rd May 2017 and 15th May 2017.

For the CCI measurements, three plants were marked in four plots within replicate (block) two. This included 0 N, 300 N for the dry treatment and 0 N, 300 N for the irrigated treatment making for a total of 12 marked plants. On the 25th November 2016, the first

leaves were marked and measured. On this date the newest emerging leaf was marked for each plant with a wire tie around the stem and a black felt tip pen on the edge of the leaf. Every two to three weeks the newest emerging leaf was marked. The oldest leaf was marked with a black felt pen, second leaf was marked with a orange felt pen, third was black and fourth was orange, making for a sequential pattern. As the oldest leaf died, date was recorded. This meant up to five leaves were alive and being measured on each plant every week. Marked leaves of a plant at the end of the experiment are shown in Appendix 3. Chlorophyll was then measured by snapping the chlorophyll meter onto one side of the marked leaf five times in order to get five CCI readings. These five readings for each plant were then averaged to give a CCI reading. The operation of device is shown in Appendix 4.

3.8 Calculations

3.8.1 Fresh matter and dry matter

Fresh matter (FM) and dry matter (DM) were determined from the mean of each plot on the harvest dates. Sub sample DM% was multiplied by whole sample FM to give total DM. The proportion of DM of root, petiole, leaf and dead organs from the sub sample measurements were multiplied by the total DM of the sample to give grams DM of respective organs. Whole sample DM was divided by sample area (m^2) to give total g m^{-2} DM. Total g m^{-2} DM was then multiplied by the proportion of DM of each organ to give kg ha^{-1} and then multiplied by 1000 to give t ha^{-1}.

Accumulated DM yields were fitted against thermal time using a Gompertz curve. The time corresponding to 5% and 95% of final DM yields, was calculated based on the curve fitted to each plot. Linear growth rates (LGR) kg ha^{-1} ^{o}Cd, were also calculated for each plot. This was done by fitting a linear regression between accumulated DM and thermal time using the data points in between 5% and 95% final yield for each plot.

3.8.2 Thermal time

Thermal time (Tt, ^{o}Cd) was calculated using Equation 3 and Equation 4. Daily average air temperature (T_{mean}) and a base temperature (T_{base}) of 0 ^{o}C were used as reported by

Chakwizira *et al.* (2016) for fodder beet. Cumulative thermal time was calculated by summing daily Tt.

3.8.3 Radiation interception

Radiation interception (R/R_o) was measured using the NDVI data (Section 3.7.2). Total incident radiation data (R_o) from the weather station (Section 3.5.2) and NDVI was used to calculate radiation intercepted (MJ^{-2}) by the canopy. A sigmoidal curve fitted for every plot was used to determine daily values of radiation interception. The curve was fitted against thermal time. After emergence, the crop experienced a linear phase of canopy expansion where it quickly reached maximum radiation interception. After this the canopy had a constant phase at maximum canopy ground cover. The total radiation intercepted by the crops were calculated by multiplying daily incident radiation values (R_o) against daily radiation intercepted (R/R_o) from crop emergence to final harvest on the 17th May 2017.

3.8.4 Radiation use efficiency

Radiation use efficiency (RUE) was calculated by plotting total plant dry matter ($g\ m^{-2}$) at final harvest against cumulative radiation interception (MJ^{-1}). A linear regression was then fitted, the slope indicating the RUE for respective treatments as shown by Equation 2.

3.8.5 Fraction of total DM partitioned in the root (f_{root})

The fraction of total dry matter partitioned in the root (f_{root}) was calculated by using Equation 8:

Equation 8: $$f_{root} = \frac{DM_{root}}{DM_{total}}$$

The fraction of total dry matter partitioned in the root was then plotted against accumulated thermal time from crop emergence in order to determine differences among treatments.

3.8.6 **Statistical analysis**

The experiment was set as a randomized completed block design with six treatments and four replicates. Statistical analysis was carried out using GenStat version 18 (VSN International). A two way analysis of variance (ANOVA) was used to determine significant differences between treatments. Least significant differences (LSD) at P 0.05 were used to separate mean differences from ANOVA.

4 RESULTS

4.1 Total crop dry matter

Total dry matter for the nitrogen and water treatments are shown in Table 4 for each of the six harvests. Total, leaf, petiole, root and dead dry matter are shown in Appendix 7. At final harvest (17th May 2017) there was 98% higher total dry matter (P<0.001) in the irrigated treatment (28.31 t ha^{-1} DM) compared with the dry treatment (14.31 t ha^{-1} DM). A photo of the roots for each nitrogen and water treatment at final harvest is shown in Plate 5. A bird's eye view photo of the entire experimental site two days prior to final harvest is shown in Appendix 8.

For the dry treatment, the 300 N treatment increased dry matter production (P<0.001) by 25% (15.81 t ha^{-1}) compared with the control (0 N) (12.62 t ha^{-1}). There was no significant effect of 50 N on dry matter production. For the irrigated treatment, both the 50 N and 300 N treatments increased dry matter production (P<0.001) by 18% (29.44 t ha^{-1}) and 23% (30.58 t ha^{-1}), respectively, compared with the control (24.92 t ha^{-1}). However there was no significant difference between 50 N and 300 N for both water treatments.

On average the irrigated treatment had significantly higher (P <0.001) total dry matter than the dry treatment in five of the six harvests. There was a significant effect of nitrogen treatment on total dry matter 100 DAP (P<0.027), 183 DAP (P<0.004) and at final harvest, 211 DAP (P<0.001).

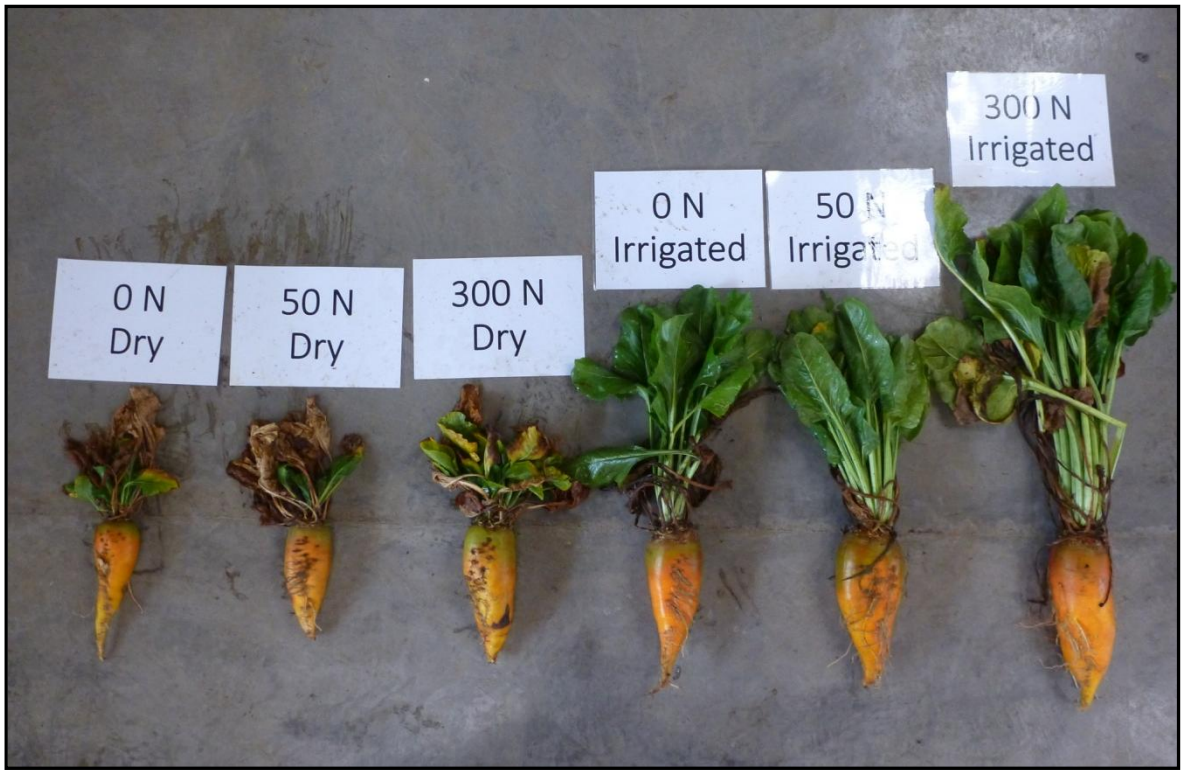

Plate 5: Image of fodder beet plants for two water and three nitrogen treatments water applied to fodder beet crops grown at Lincoln, Canterbury, New Zealand, 2016-2017. Photo was taken on the 17th May 2017 at final harvest.

Table 4: ANOVA for total dry matter (t ha^{-1} DM) at six sequential harvest dates for two water and three nitrogen treatments applied to the fodder beet crops grown at Lincoln, Canterbury, New Zealand, 2016-2017. Overall means for dry and irrigated yields are included.

Treatment/Harvest Date (Days after planting)	19th Dec 2016 (62)	26th Jan 2017 (100)	22nd Feb 2017 (127)	22nd Mar 2017 (155)	19th Apr 2017 (183)	17th May 2017 (211)
Dry+0N	0.89	4.36	8.72	9.99	12.36	12.62
Dry+50N	0.75	5.55	10.40	9.84	12.06	14.50
Dry+300N	0.81	5.63	9.51	11.60	14.43	15.81
Average Dry	0.81	5.18	9.54	10.48	12.95	14.31
Irrigated+0N	1.14	8.88	15.05	16.73	21.14	24.92
Irrigated+50N	0.81	8.78	14.98	20.63	25.61	29.44
Irrigated+300N	0.86	12.76	17.85	26.16	29.50	30.58
Average Irrigated	0.94	10.14	15.96	21.17	25.42	28.31
Nitrogen P value	ns	0.027	ns	0.001	0.004	0.001
Water P value	ns	<0.001	<0.001	<0.001	<0.001	<0.001
N*W P value	ns	ns	ns	ns	ns	ns
Nitrogen LSD 5%	0.5059	1.902	1.753	5.99	2.806	2.137
Water LSD 5%	0.4131	1.553	1.432	4.89	2.291	1.745
N*W LSD 5%	0.7155	2.689	2.48	8.48	3.968	3.022

4.2 Fodder beet total yield over thermal time

A gormpertz curve was used to describe the relationship between dry matter production and accumulated thermal time (adjusted R^2= 0.97) for all water and nitrogen treatments as shown in Figure 5 (refer to Appendix 5 for curves displayed in the same Figure). There was a trend of higher accumulated thermal time (P<0.077) in the irrigated treatment (2760 ^{o}Cd or 190 DAP) compared with the dry treatment (2602 ^{o}Cd or 177 DAP) at 95% final crop yield (Table 5). However there was no significant effect of nitrogen treatments on the amount of thermal time required to reach 5 and 95% final yield.

The rate of maximum dry matter accumulation (LGR) was 89% higher (P <0.001) in the irrigated treatment (12.1 kg ha^{-1} ^{o}Cd) than in the dry treatment (6.44 kg ha^{-1} ^{o}Cd) (Table 5). In the dry treatment, the 300 N treatment increased LGR (P<0.001) by 59% (8.19 kg ha^{-1} ^{o}Cd) compared with the control (5.19 kg ha^{-1} ^{o}Cd). However there was no significant effect of 50 N on LGR. In the irrigated treatment the 50 N and 300 N nitrogen treatments increased LGR (P<0.001) by 29% (12.5 kg ha^{-1} ^{o}Cd) and 46% (14.2 t ha^{-1}), respectively, compared with the control (9.72 kg ha^{-1} ^{o}Cd). The 300 N treatment increased LGR by 13% compared with 50 N.

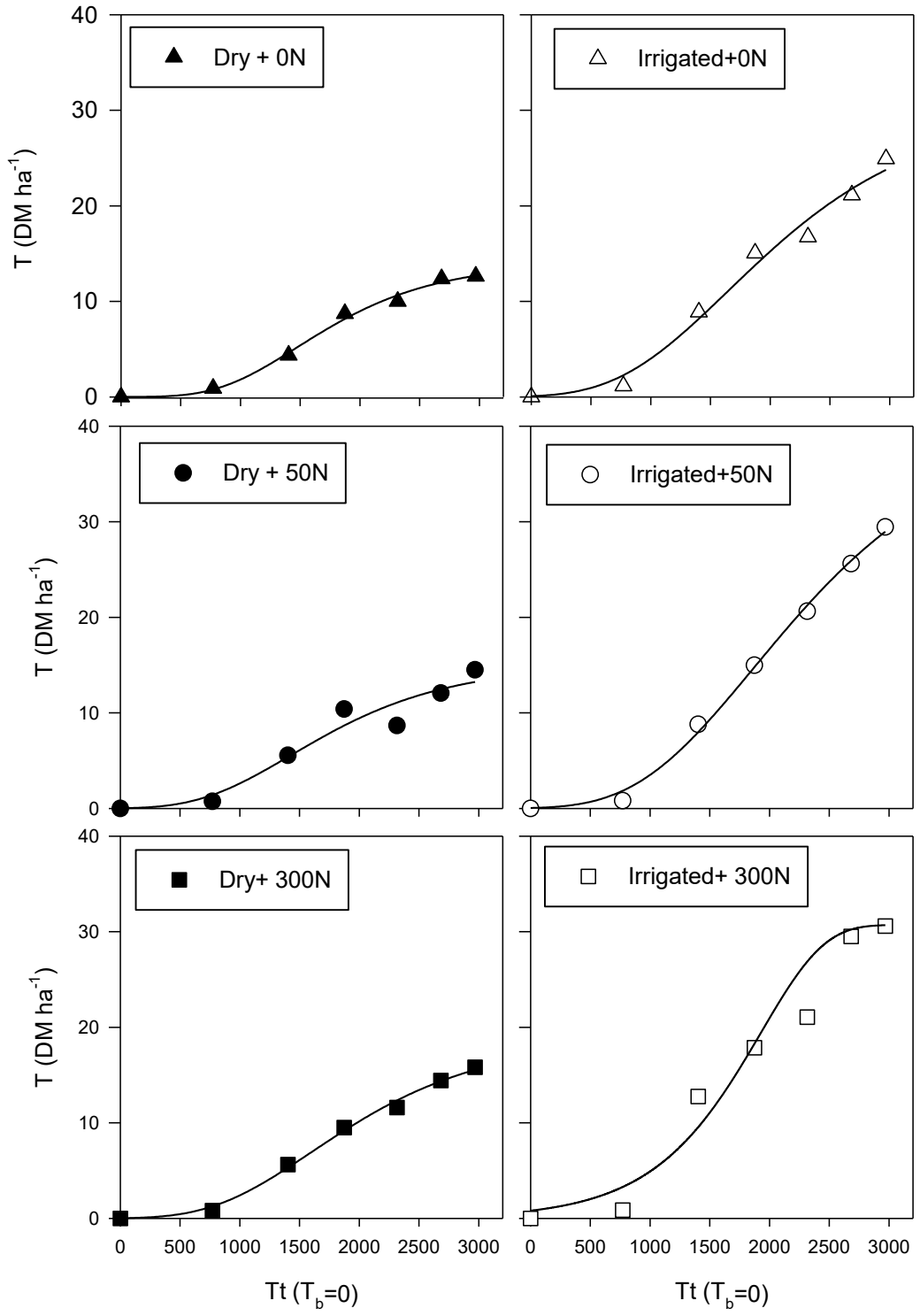

Figure 5: Total dry matter (t ha^{-1}) measured from 27th October 2016 to 17th May 2017 against thermal-time from crop emergence measured in ^{o}Cd for two water and three nitrogen treatments applied to fodder beet crops grown at Lincoln, Canterbury, New Zealand, 2016-2017.

Table 5: Parameters of the sigmoid curves shown in Figure 5 that correspond to accumulated total DM for two water and three nitrogen treatments applied to fodder beet crops grown from October 2016 to May 2017 at Lincoln, Canterbury, New Zealand,. Values bracketed represent days after planting (DAP).

Treatment	5% total yield DM (°Cd)	95% total yield DM (°Cd)	LGR(kg ha^{-1} °Cd)
Dry+0N	479 (42)	2616 (178)	5.19
Dry+50N	502 (44)	2604 (177)	5.92
Dry+300N	715 (58)	2585 (175)	8.19
Average Dry	565 (49)	2602 (177)	6.44
Irrigated+0N	568 (49)	2782 (191)	9.72
Irrigated+50N	698 (57)	2800 (193)	12.52
Irrigated+300N	718 (58)	2698 (184)	14.17
Average Irrigated	661 (54)	2760 (190)	12.14
Nitrogen P value	ns	ns	0.001
Water P value	ns	0.077	<0.001
N*W P value	ns	ns	ns
Nitrogen LSD 5%	196	217.6	1.672
Water LSD 5%	160.1	177.7	1.365
N*W LSD 5%	277.2	307.7	2.364

4.3 Radiation interception (R/R_o)

As shown in Figure 6 a sigmoid curve was used to describe the relationship of radiation interception (R/R_o) over the crop duration for each water and nitrogen treatment. The average R^2 for all treatments except for the 300 N dry treatment (R^2=0.84) was 0.95. The R/R_o at 95% final canopy ground cover was 67% higher (P<0.001) in the irrigated (80.8%) than in the dry crops (48.4%) (Table 6). In the dry treatment, the 50 N and 300 N nitrogen treatments increased R/R_o (P<0.001) by 14% (46.6%) and 40% (57.5%), respectively, compared with the control (41.0%). The 300 N treatment increased R/R_o by 23% compared with 50 N. In the irrigated treatment, 50 N and 300 N increased R/R_o by 9% (80.5%) and 21% (88.5%), respectively, compared with the control (73.2%) (P<0.001). The 300 N treatment increased R/R_o by 10% compared with 50 N (P<0.001).

The irrigated treatment had no significant effect on the time to 95% of final R/R_o (or time to 95% of final canopy ground cover (Table 6). For the dry treatment, 300 N increased time to R/R_o by 190 ^{o}Cd or 19 days after planting (DAP) compared with the control (P<0.001). The 50 N treatment had no significant effect on time to R/R_o 95% compared with the control. For the irrigated treatment, 300 N increased time to R/R_o 95% by 236

^{o}Cd or 15 DAP compared with the control. Similarly, like in the dry treatment, the 50 N irrigated treatment had no significant effect on time to R/R_o. Both nitrogen and water application had no significant effect on rate of canopy expansion. This was on average 0.0024 (% $^{o}Cd^{-1}$) (Table 6).

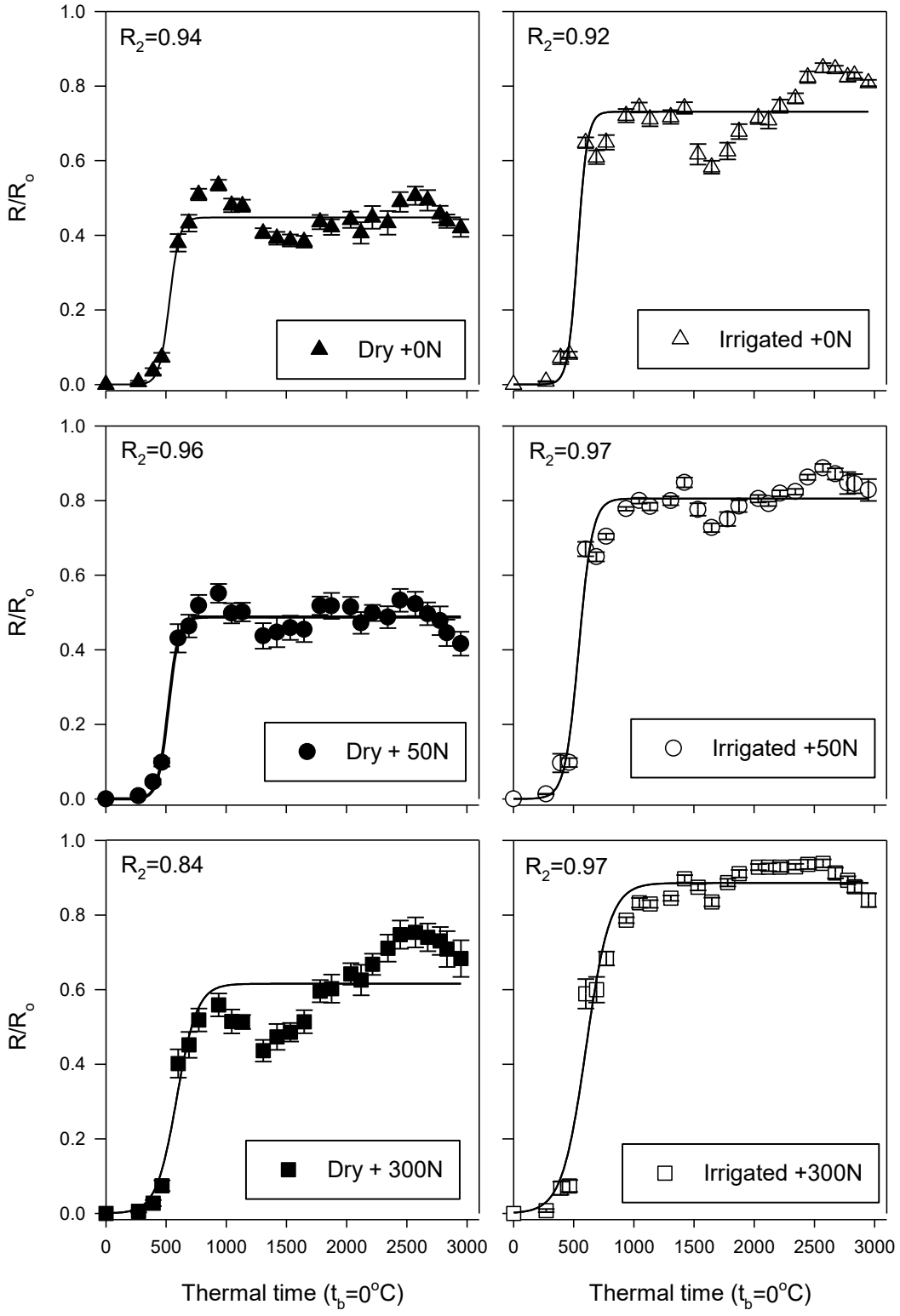

Figure 6: Radiation interception (R/Ro) measured from 27th October 2017 to 17th May 2017 against thermal-time from crop emergence measured in °Cd for two water and three nitrogen treatments applied to fodder beet crops grown at Lincoln, Canterbury, New Zealand, 2016-2017. R/Ro ranges from '0' (no interception) to "1" (100% interception).

Table 6: Parameters of sigmoid curves shown in Figure 6 that correspond to radiation interception, or canopy ground cover (R/Ro), for two water and three nitrogen treatments applied to fodder beet crops grown from October 2016 to May 2017 at Lincoln, Canterbury, New Zealand. Values bracketed represent days after planting (DAP). R/R_o represents the percentage canopy ground cover at 95% of the final ground cover. Time to R/R_o represents the amount of thermal time required to reach 95% final ground cover. The rate of increase corresponds to the linear growth phase of the canopy.

Treatment	R/Ro 95% (%)	Time to R/Ro 95%	Rate of increase (% $^{o}Cd^{-1}$)
Dry+0N	41.0	651 (54)	0.00240
Dry+50N	46.6	654 (54)	0.00244
Dry+300N	57.5	841 (73)	0.00207
Average Dry	48.4	715(49)	0.00230
Irrigated+0N	73.2	657(54)	0.00237
Irrigated+50N	80.5	712(58)	0.00248
Irrigated+300N	88.6	893 (69)	0.00267
Average Irrigated	80.8	754 (52)	0.00251
Nitrogen P value	<.001	<.001	ns
Water P value	<.001	ns	ns
N*W P value	ns	ns	ns
Nitrogen LSD 5%	3.157	102.7 (6.0)	0.000522
Water LSD 5%	2.578	83.9 (4.9)	0.000427
N*W LSD 5%	4.465	145.3 (8.5)	0.000739

4.4 Accumulated radiation intercepted

Figure 7 and Figure 8 show the accumulated radiation intercepted against thermal time and days after planting, respectively. Irrigated plants (2097 MJ m^{-2}) intercepted 55% more radiation ($P<0.001$) than dry plants (1350 MJ m^{-2}) at final harvest. In the dry treatment, the 50 N and 300 N nitrogen treatments increased radiation intercepted by 14% (1298 MJ m^{-2}) and 42% (1615 MJ m^{-2}), respectively, compared with the control (1138 MJ m^{-2}) ($P<0.001$). The 300 N treatment increased radiation intercepted by 24% compared with 50 N ($P<0.001$). In the irrigated treatment 50 N and 300 N nitrogen treatments increased radiation intercepted by 11% (2212 MJ m^{-2}) and 17% (2253 MJ m^{-2}), respectively, compared with the control (1927 MJ m^{-2}) ($P<0.001$). The 300 N treatment increased radiation intercepted by 7% compared with 50 N.

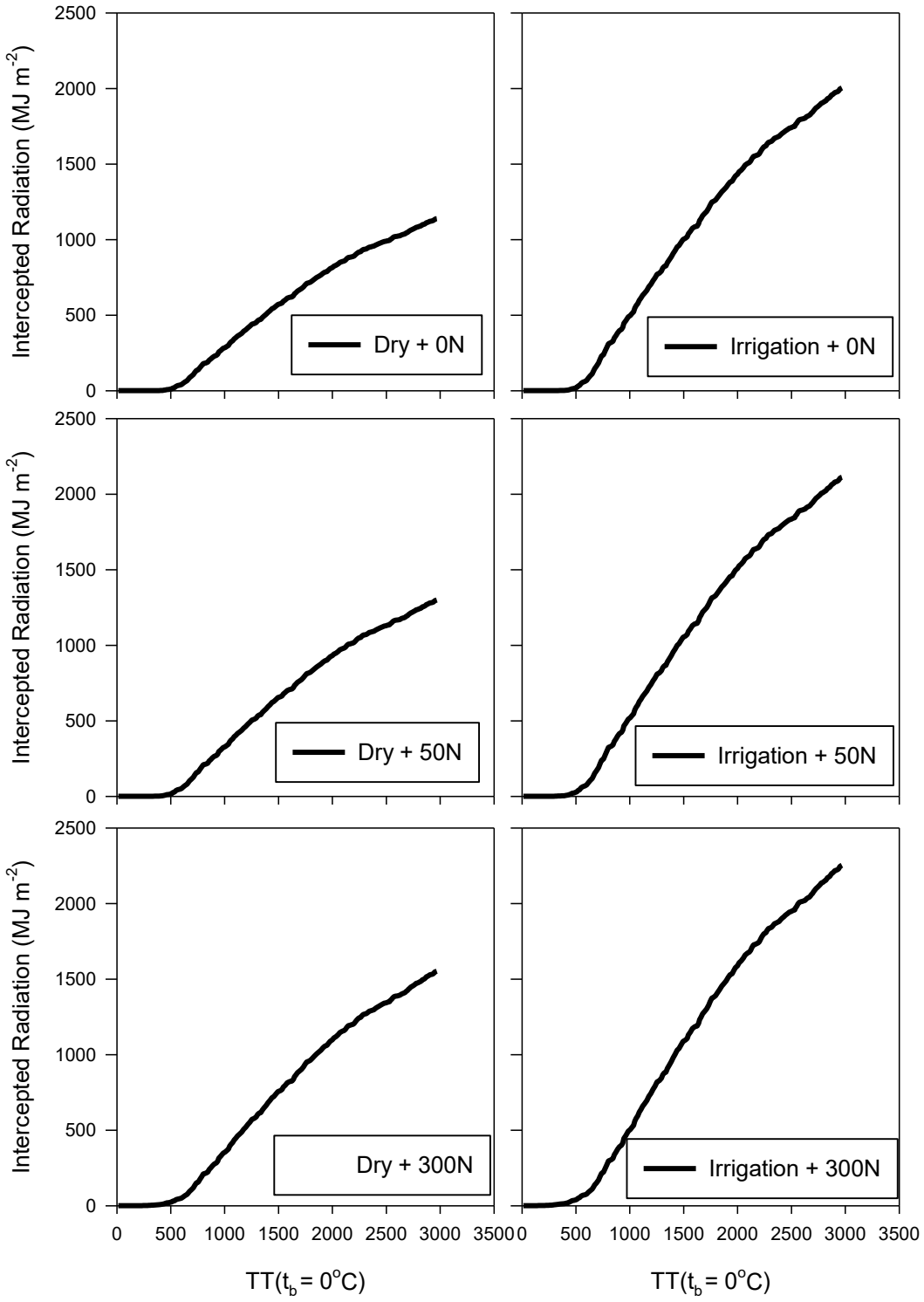

Figure 7: Total cumulative intercepted radiation (MJ m^{-2}) measured from 27th October 2017 to 17th May 2017 against thermal-time from crop emergence measured in ^{o}Cd from crop emergence for two water and three nitrogen treatments applied to fodder beet crops grown at Lincoln, Canterbury, New Zealand, 2016-2017.

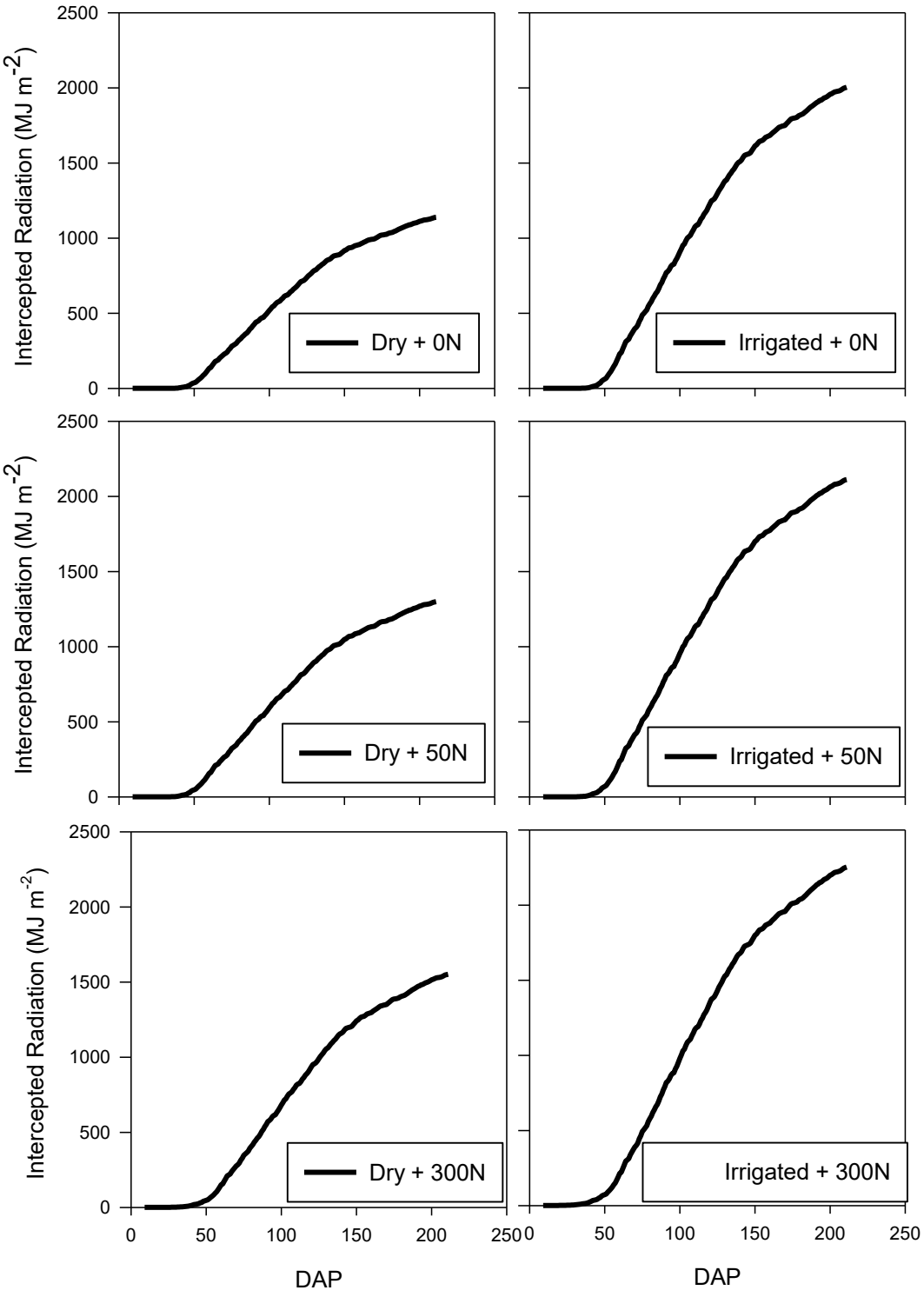

Figure 8: Total cumulative intercepted radiation (MJ m^{-2}) measured from 27th October 2017 to 17th May 2017 against days after planting (DAP) from crop emergence for two water and three nitrogen treatments applied to fodder beet crops grown at Lincoln, Canterbury, New Zealand, 2016-2017.

4.5 Radiation use efficiency

As shown in Figure 9 a linear regression was fitted to total plant dry matter (g m^{-2}) against cumulative the radiation intercepted. RUE was calculated as the slope of the linear regression. The irrigated treatment increased RUE (P<0.001) by 27% (1.47 g DM MJ^{-1}) compared with the dry treatment (1.16 g DM MJ^{-1}). There was no effect of nitrogen on radiation use efficiency, (refer to Appendix 6 for individual treatment regressions). There was an interaction between water and nitrogen (P<0.036) on RUE, however RUE was mostly influenced by the water treatment.

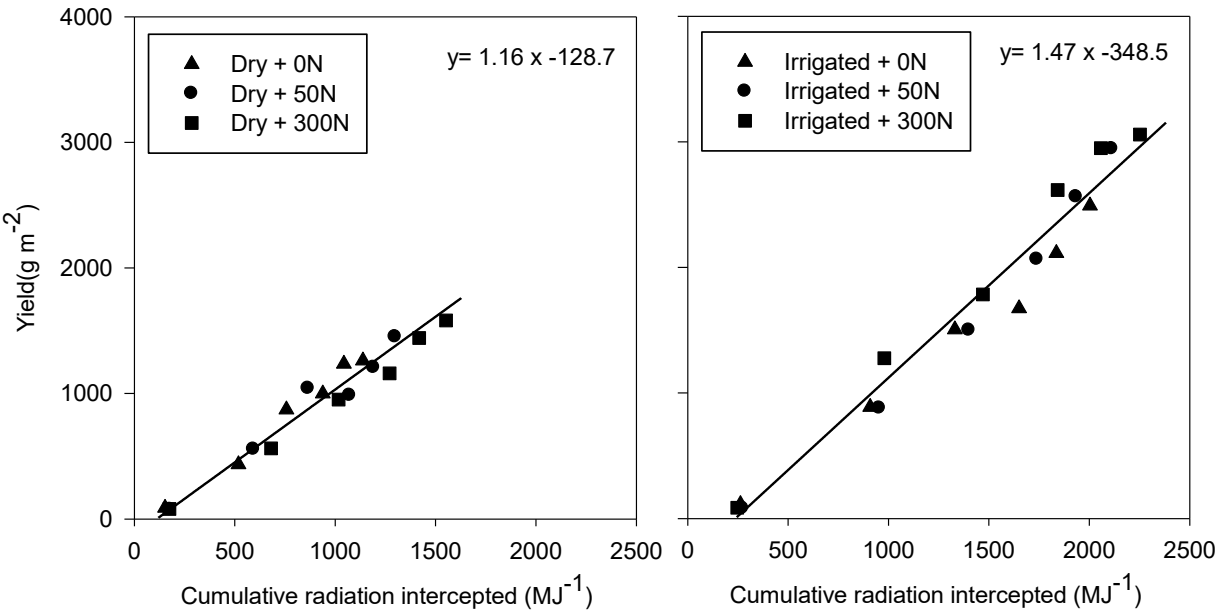

Figure 9: Total cumulative dry matter (DM) measured from 27th October 2017 to 17th May 2017 against cumulative radiation intercepted (MJ^{-1}) from crop emergence for two water and three nitrogen treatments water and nitrogen treatments applied to fodder beet crops grown at Lincoln, Canterbury, New Zealand, 2016-2017. A regression line was fitted to give radiation use efficiency as displayed by the equation. RUE values and x intercept are shown in (Table 7). Equation displayed in figure is average dry and irrigated treatment.

Table 7: ANOVA for RUE parameters and x intercept from linear regression as displayed in Figure 9 for two water and three nitrogen treatments applied to fodder beet crops grown from October 2016 to May 2017 at Lincoln, Canterbury, New Zealand.

Treatment	Slope (RUE)	Intercept at x
Dry+0N	1.26	91.08
Dry+50N	1.15	94.78
Dry+300N	1.08	180.87
Average Dry	1.16	122.24
Irrigated+0N	1.35	195.19
Irrigated+50N	1.54	315.33
Irrigated+300N	1.52	185.05
Average Irrigated	1.47	231.86
Nitrogen P value	ns	ns
Water P value	<.001	0.01
N*W P value	0.036	ns
Nitrogen LSD 5%	0.135	101.10
Water LSD 5%	0.110	82.50
N*W LSD 5%	0.191	142.90

4.6 Fraction of total dry matter partitioned in the root

The root fraction of total dry matter (f_{root}) is shown in Figure 10. At final harvest there was 5.4% greater f_{root} ($P<0.001$) in the dry treatment (85.0%) compared with the irrigated treatment (79.6%). In the dry treatment the 300 N treatment increased f_{root} ($P<0.001$) by 1.2% (85.6%) compared with the control (84.4%). There was no effect of 50 N on f_{root}. In the irrigated treatment 300 N decreased ($P<0.001$) f_{root} by 8.3% (73.9%) compared with the control (84.4%). There was no significant effect of 50 N on f_{root}. The effect of the interaction between water and nitrogen on HI for all treatments was deemed significant ($P<0.001$).

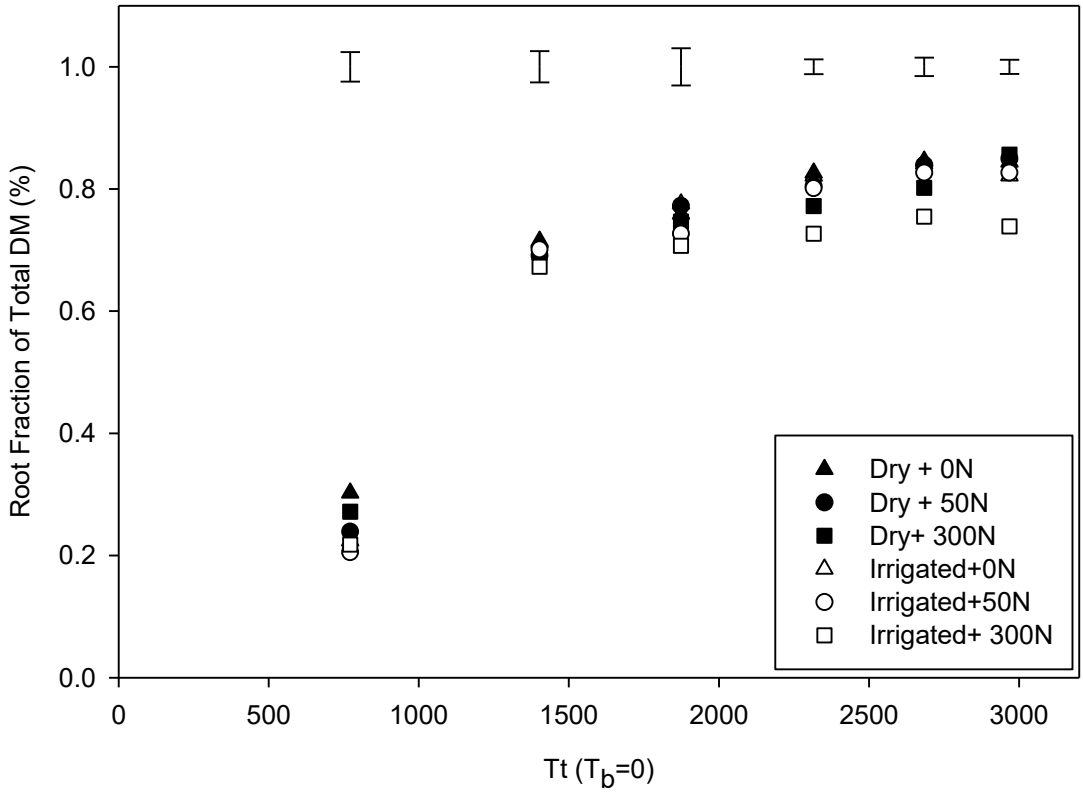

Figure 10: Fraction of dry matter partitioned in root (%) measured from 27th October 2016 to 17th May 2017 against thermal-time from crop emergence measured in ^{o}Cd for two water and three nitrogen treatments applied to fodder beet crops grown at Lincoln, Canterbury, New Zealand, 2016-2017.

4.7 Above ground dry matter

4.7.1 Leaf

Leaf and petiole dry matter over the crop growing season for all water and nitrogen treatments is shown in Figure 11 and Appendix 7. There was a significant interaction between water and nitrogen on leaf dry matter yield (P<0.002). The water treatment was the most influential factor on leaf dry matter yield. At final harvest there was 269% higher leaf dry matter (P<0.001) in the irrigated treatment (1.88 t ha^{-1}) compared with the dry treatment (0.70 t ha^{-1}). In the dry treatment 300 N increased (P<0.001) leaf dry matter yield by 63% (0.94 t ha^{-1}) compared with the control (0.58 t ha^{-1}). In the irrigated treatment 50 N and 300 N increased (P<0.001) leaf dry matter yield by 26% (1.66 t ha^{-1}) and 201% (2.65 t ha^{-1}), respectively, compared with the control (1.32 t ha^{-1}).

4.7.2 Petiole

There was significant interaction between water and nitrogen on petiole dry matter yield (P<0.001). The water treatment has the greatest influence on petiole DM yield. The

Irrigated treatment had 662% greater ($P<0.001$) petiole dry matter (2.01 t ha^{-1}) compared with the dry treatment (0.30 t ha^{-1}). In the dry treatment 50 N and 300 N increased ($P<0.001$) petiole dry matter by 37% (0.28 t ha^{-1}) and 207% (0.42 t ha^{-1}), respectively, compared with the control (0.20 t ha^{-1}). In the irrigated treatment 50 N and 300 N increased petiole dry matter ($P<0.001$) by 31% (1.59 t ha^{-1}) and 265% (3.22 t ha^{-1}), respectively, compared with the control (1.22 t ha^{-1}).

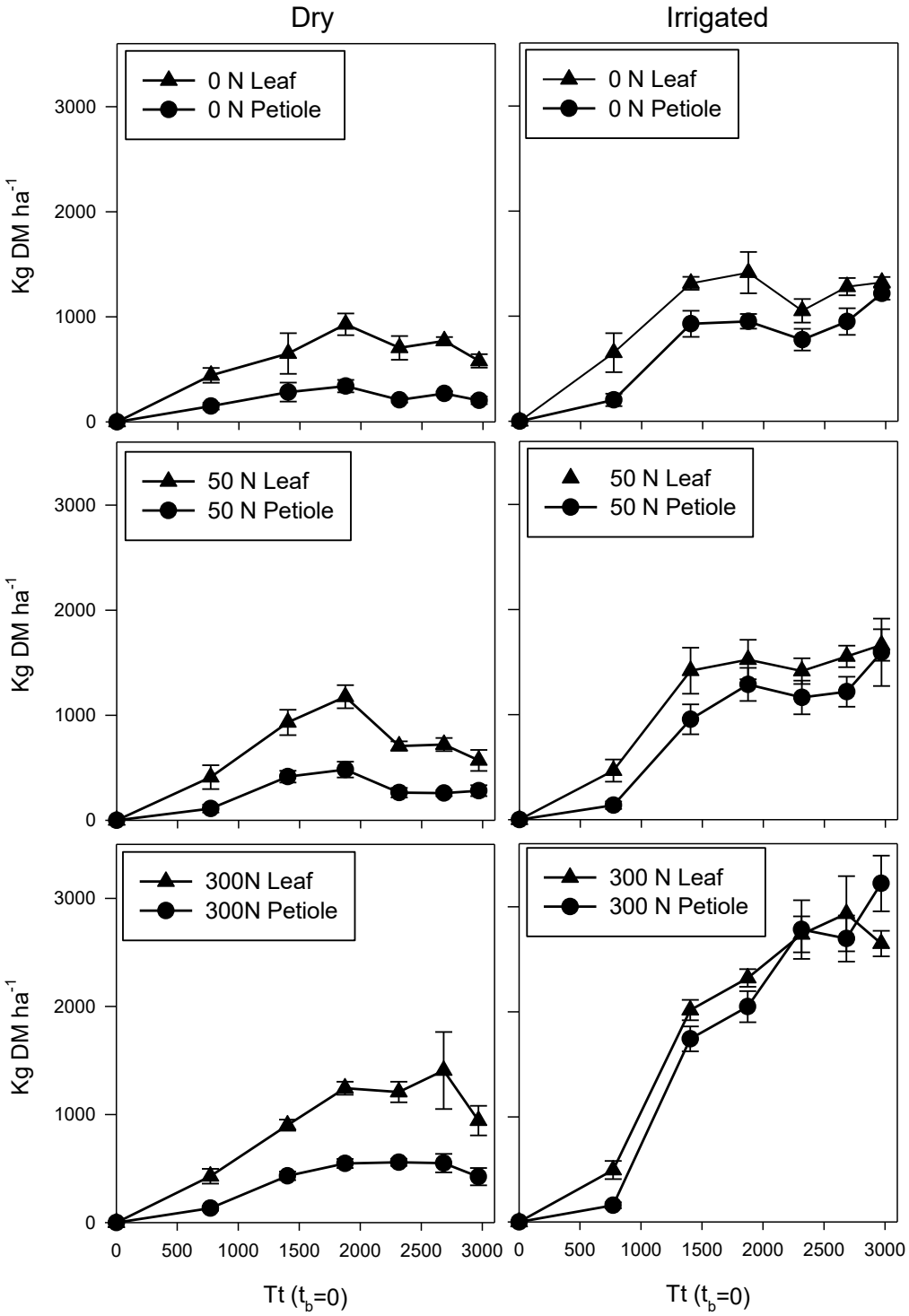

Figure 11: Leaf and petiole dry matter (kg ha^{-1}) measured from 27th October 2016 to 17th May 2017 against thermal-time from crop emergence measured in ^{o}Cd for two water and three nitrogen treatments applied to fodder beet crops grown at Lincoln, Canterbury, New Zealand, 2016-2017.

4.8 Leaf Chlorophyll

On average, the dry treatment had 30% higher (P<0.001) leaf chlorophyll (370.5 µmol m^{-2}) compared with the irrigated treatment (286.2 µmol m^{-2}) (Figure 12). The dry 300 N treatment increased (P<0.001) leaf chlorophyll by 10.3% (388.6 µmol m^{-2}) compared with the control (352.3 µmol m^{-2}). The irrigated 300 N treatment increased (P<0.001) leaf chlorophyll by 13.8% (304.7 µmol m^{-2}) compared with the control (267.6 µmol m^{-2}). The time of sampling (measured in thermal time) also influenced leaf chlorophyll concentration (P<0.001).

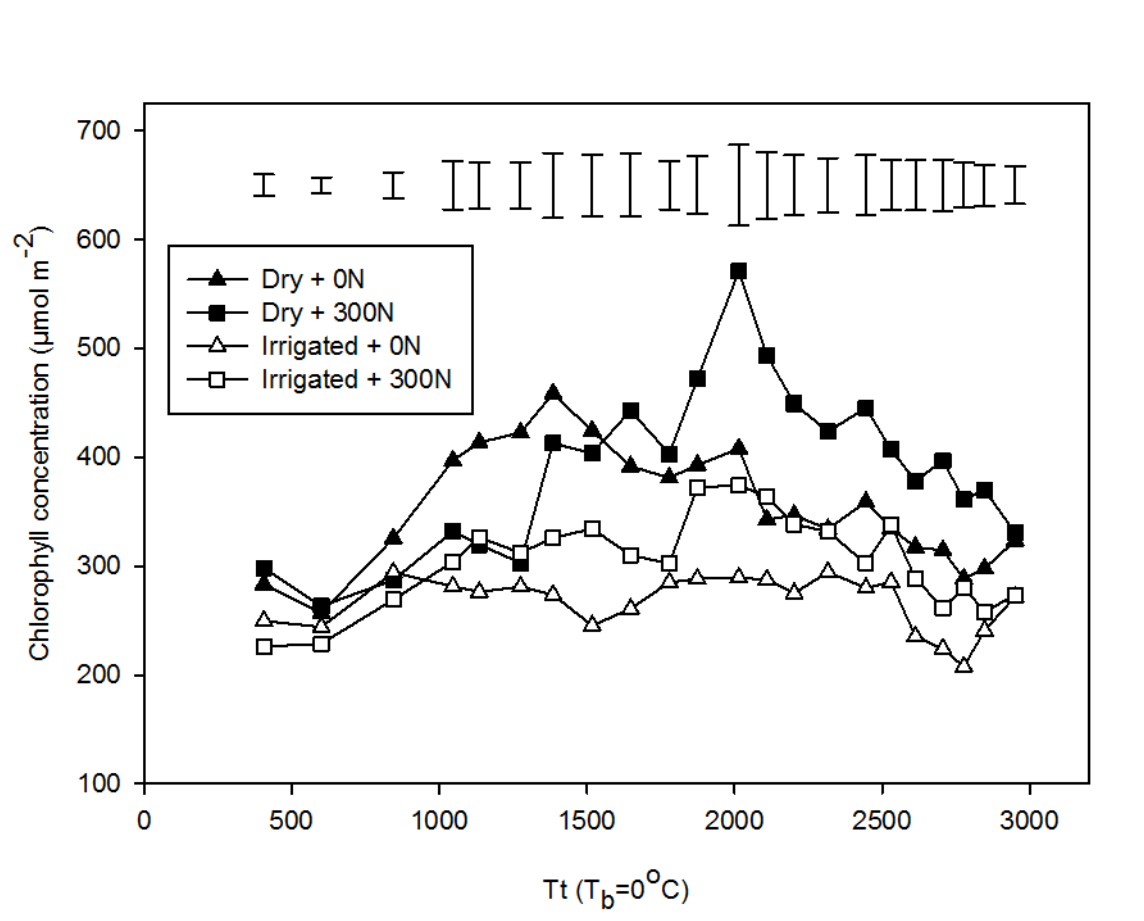

Figure 12: Chlorophyll concentration of marked leaves (µmol m^{-2}) measured from 25th November 2016 to 15th May 2017 against thermal-time measured in °Cd for two water and two nitrogen treatments applied to fodder beet crops grown at Lincoln, Canterbury, New Zealand, 2016-2017. Data was collected from 3 marked plants within each respective treatment in rep 2.

5 DISCUSSION

5.1 Yield differences between treatments

5.1.1 Water

At final harvest, there was 98% greater dry matter in the irrigated compared with the dry treatment (Table 4). Low water availability is a major cause of crop yield reduction (Boyer, 1982). Various functions of water in plants include maintaining cell turgidity for structure and growth, transporting nutrients and organic compounds throughout the plant. It also used in many reactions including photosynthesis and is largely used for daily transpiration (White and Hodgson, 1999). It is important to note the dry treatment only source of water was 10 mm, received at each of the fertiliser applications including the control. In a more realistic situation rainfall would be a major factor, which is removed as the experiment was situated inside a rain shelter. Therefore, there are very wide yield differences due to differences in water availability.

Water stress suppresses the duration of plant photosynthesis. The irrigated treatment (2760 ^{o}Cd or 190 DAP) accumulated higher thermal time than the dry treatment (2602 ^{o}Cd or 177 DAP) to reach 95% yield (Table 5). This shows that due to greater water availability irrigated plants grew for 13 more days after planting to reach 95% yield. Water is essential to maintain turgor pressure. When plant cells dehydrate pressure is lost and growth is impeded (Farooq *et al.*, 2009). Water stress greatly suppresses photosynthetic growth rate. The rate of maximum dry matter accumulation or linear growth rate (LGR), as shown in Table 5, was 89% higher in irrigated (12.14 kg ha^{-1} ^{o}Cd) than in the dry treatment (6.44 kg ha^{-1} ^{o}Cd). This indicates that irrigated plants grew more efficiently and at a higher rate. As shown in Figure 1 leaf expansion is inhibited under a slight decrease in water potential. As water potential decreases, photosynthetic rate decreases, all due to water stress (Taiz and Zeiger, 2010).

5.1.2 Nitrogen

Nitrogen is an essential element in promoting yield in crops. In the dry treatment 300 N increased dry matter production by 25% compared with the control (Table 4). Nitrogen is required for DNA, RNA, protein (which are the basic components of enzymes),

chlorophyll, ATP, auxins and cytokinins (Andrews *et al.*, 2013). Nitrogen is a major component in chlorophyll. Higher amounts of nitrogen lead to greater production of chlorophyll in the chloroplasts. As a result of that, the rate of photosynthesis increases and this leads to an increase in plant growth. High nitrogen application rates increased LGR. In the dry treatment 300 N increased LGR by 59% compared with the control (Table 5). There was no significant effect of 50 N on LGR, which is expected as yield did not increase between these treatments.

In fodder beet the main purpose of nitrogen is to stimulate the production of foliage canopy to allow for radiation interception especially straight after sowing. Malnou *et al.* (2006) found that 100 kg N was needed to reach 85% canopy cover in sugar beet. In this experiment, the result suggests that a higher nitrogen rate of 300 N in the dry treatment improved canopy growth for light interception in the crop, and lead to a larger increase in plant dry matter. There was no significant affect of 50 N on crop dry matter production. This suggests that 50 kg N in the dry treatment did not increase radiation interception sufficiently to cause a yield difference. In the irrigated 50 N and 300 N nitrogen treatments dry matter production increased by 18% and 23%, respectively, compared with the control. However there was no significant difference between 50 N and 300 N, which shows that higher N application was not beneficial towards reaching greater yield.

Under irrigation, high nitrogen application rates would be expected to increase canopy cover resulting in greater radiation interception. A possible reason for why 300 N did not have greater yield compared with 50 N is that the 300 N plants had reached 95% maximum yield 9 DAP or 102 ^{o}Cd before 50 N and the light intercepted at the end of the crop duration did not result in net photosynthesis. To support this theory it is to be noted that on the 19th April 2017 or 193 DAP (Table 4), 300 N irrigated had significantly greater yield. It was only until a month later on the 17th April 2017 or 211 DAP that the 50 N treatment had similar total yield to the 300 N treatment. Under irrigation increasing nitrogen application rate increased LGR, which was also found in the dry treatment. In irrigated 50 N and 300 N treatments LGR increased by 29% and 46%, respectively, compared with the control (Table 5). This result shows that 300 N grew faster than the 50 N during its linear growth phase, but experienced a slower growth rate near the end of

the crop duration. The 50 N did not experience this decline in photosynthetic growth rate and was able to reach a similar yield to the 300 N treatment as shown by the gompertz curve in Figure 5. This further supports that fodder beet grown with high N and adequate water availability accumulated dry matter at a faster rate and ceased growth earlier.

A possible reason for why nitrogen increased dry matter production is that in water stressed conditions the crop may stop taking up N. Firstly because of a reduction of transpiration. Secondly once the plant has extracted all N out of the macro pores, N is only available in the smaller pores which the roots cannot extract as too much pressure is required to utilise it. Once irrigation is restored it leads to increased transpiration and, or water is refilled into the larger pores leading to the movement of N into the rooting zone, making it more available for uptake (Gonzalez-Dugo *et al.*, 2010). Increased N uptake after a drought period has been attributed to the stimulation of soil microbial activity and mineralisation of soil organic N due to the availability of moisture (Wright and Davison, 1964). Therefore due to increased water availability it increases the ability to take up either fertiliser and soil N which leads to large increases in growth. This could also explain why in the 50 N dry treatment, LGR did not significantly increase whereas it did in the irrigated 50 N irrigated treatment. The 300 N under dry conditions had a significant increase in yield because it may have meant that enough N was available within the macropores and therefore did not need more water to extract N within the smaller pores.

5.2 Explanation of crop yield differences provided from yield components

Crop growth and yields are related to crop duration which is dependent on crop management, cultivar and climate (Kooman *et al.*, 1996). Accordingly, if crop management is kept at an optimum level, differences in yield can be expressed based on the amount of radiation intercepted by the crop. The differences in yield can be shown by comparing radiation intercepted, radiation use efficiency and dry matter partitioning.

An equation by Jamieson *et al.* (2004) and Oliveira *et al.* (2016) conveys potato dry matter growth which is adaptable to most plants including fodder beet as shown in Equation 1.

5.2.1 **Fractional canopy cover and radiation interception**

5.2.1.1 Water

Water stress severely restricts canopy cover leading to large decreases in radiation interception and consequently yield. The 95% maximum R/R_o or fractional canopy cover was 67% higher in the irrigated than in the dry plants (Table 6). As a result of increased canopy cover irrigated plants intercepted 55% greater radiation than dry plants as shown in Figure 7 and Figure 8.

A reason for higher canopy cover includes greater leaf area due to adequate water supply. After initiation, the developing leaf enters a stage of growth where it is dominated by two different processes of cell division and cell expansion (Hay and Walker, 1989). Firstly cell division involves the production of new cell material. Secondly cell expansion is driven by turgor pressure within the cell, greater pressure means more water within the cell which drives cell growth (Dale, 1988). Leaf area expansion rate (LAER) is significantly reduced by mild water deficits that would normally not affect photosynthesis. In fodder beet Chakwizira *et al.* (2016) found that the LAER in unconstrained water and N supply was 0.0025 $m^2\ m^2\ {}^oCd^{-1}$ and 0.0034 $m^2\ m^2\ {}^oCd^{-1}$ in two identical experiments with differing location. When water was limited LAER was reduced by 32% and 26%. Therefore, water stress is the most important factor influencing yield in this experiment as it affects leaf expansion rate which negatively affects fractional canopy cover. Water had no effect on the rate at which the canopy developed and expanded as indicated by the insignificance of time to R/R_o 95% (Table 6).

5.2.1.2 Nitrogen

Plant nitrogen availability influences the rate of leaf expansion and final leaf size. In the dry treatment 50 N and 300 N treatments increased R/R_o by 14% and 40%, respectively, compared with the control (Table 6). As a result of increased canopy cover, in the 50 N and 300 N dry treatments, light intercepted by these crops increased by 14% and 42%, respectively, compared with the control (Figure 7 and Figure 8). Morton and Watson (1948) found that in sugar beet, plants receiving high nitrogen supply had more and larger cells compared with leaves of low nitrogen supply. This shows that nitrogen supply affects both cell extension and cell division of the leaf resulting in greater leaf area. Also,

in the 50 N and 300 N irrigated treatments R/R_o increased by 9% and 21%, respectively, compared with the control. As a result of increased canopy cover, in the irrigated treatment 50 N and 300 N treatments increased radiation intercepted by 11% and 17%, respectively, compared with the control.

Reduced N supply in fully expanded leaves leads to a decrease in the number of cells, leaf area per cell and cell area (Trapani *et al.*, 1999). Roggatz *et al.* (1999) showed that the stage of development when nitrogen stress is applied has a large effect on final leaf size. N stress at earlier stages of leaf development when cell division is occurring resulted in a greater decrease in final leaf size of 80%. Also in this same study low N supply resulted in lower individual leaf dry matter. Chakwizira *et al.* (2016) similarly found in fodder beet at later stages of growth, a reduction in leaf expansion rate of 50% from 0.0024 $m^2\ m^2\ {}^oCd^{-1}$ for plants supplied 200 kg N ha^{-1} to 0.0012 $m^2\ m^2\ {}^oCd^{-1}$ with 0 kg N ha^{-1}. This explains why canopy cover increased with increasing N supply in this work.

A short supply of nitrogen means that the plant cannot produce the potential number of leaves per plant, reach the potential area per leaf or maintain the nitrogen concentration in leaves and other organs necessary for unrestricted growth (Greenwood *et al.*, 1990). Due to short supply of nitrogen under stressful conditions plants may focus on the maintenance of leaf size at a cost of decreased photosynthesis per unit leaf area, or maximise productivity per unit leaf area at a cost of maximum leaf size (Vos and van der Putten, 1998). All of these results are in line with what was found in this experiment and suggest why nitrogen application increased fractional canopy cover.

In the dry treatment 300 N extended the time of canopy development by 19 DAP compared with the control. The 50 N treatment had no significant affect compared with the control. This suggests that nitrogen extended the duration of canopy expansion but only at high N rates. As the rate of canopy expansion was unaffected by water it would be expected canopy expansion would take longer as more and bigger leaves need to grow. Correspondingly within the irrigated treatment, 300 N increased the time of canopy development by 15 DAP compared with the control. Similarly, dry 50 N did not extend canopy development time.

5.3 Radiation use efficiency

5.3.1 **Water**

Water stress is detrimental to the efficiency of dry matter production. The irrigated treatment had 27% greater radiation use efficiency compared with dry treatment as shown in Figure 9. Water stress decreases RUE in both C3 and C4 species (Jamieson *et al.*, 1995a). This is because water deficits negatively influence the maintenance of cell turgidity for structure and growth (White and Hodgson, 1999). Water deficits also influence reactions including leaf photosynthesis rates which primarily cause stomata closure and under severe water deficits it increases mesophyll resistance to CO_2 diffusion (Gastal and Durand, 2000). Chakwizira *et al.* (2018) reported that in fodder beet RUE for rain fed, 0 kg N ha^{-1} crops was reduced by 25% compared with crops in unconstrained conditions. The lower RUE under was associated with reduced leaf photosynthesis rates. Jamieson *et al.* (1995a) highlights that RUE declined linearly with water deficit, however this trend was also dependant on timing and duration of the deficit. Jaggard *et al.* (2009a) found similar results in sugar beet in 1982 and 2006, RUE decreased from 1.46 g DM MJ^{-1} in irrigated to 1.26 g DM MJ^{-1} in rain fed in 1982. Similarly, in 2006 RUE decreased with 1.37 g DM MJ^{-1} in irrigated and 1.22 g DM MJ^{-1} in rain fed.

5.4 Fraction of total dry matter partitioned in the root and sink strength

5.4.1 **Water**

Greater water availability resulted in lower fraction of total dry matter partitioned in the root (f_{root}) as greater canopy ground cover acts as a larger sink for assimilates. This was shown in this experiment as the dry treatment had 5.4% greater percentage dry matter partitioned in the root compared with the irrigated plants as shown in Figure 10. The irrigated treatment had 67% greater canopy ground cover compared with the dry treatment that led to greater sink strength for assimilates, in order to maintain the above ground biomass. This is at the expense of energy going to the root therefore percentage wise there is more energy proportionally going into the leaves and stem. At final harvest there was 269% higher leaf dry matter and 662% higher petiole dry matter in irrigated plots compared with dry plots (Figure 11). This supports that there is a significantly larger canopy to maintain. Sink strength can be attributed to the number of cells in a sink organ

and the physiological age of the organ (Marcelis, 1996). With increasing sink size there is greater sink strength. Therefore, greater water availability results in a bigger above ground biomass, which acts as a larger sink for photoassimilates. This results in a lower DM percentage in the root compared with a plant that is water stressed.

5.4.2 **Nitrogen**

Similarly to the irrigation treatment, greater nitrogen availability increased canopy ground cover which leads to a greater sink for assimilates above ground. However, the dry 300 N treatment increased f_{root} by 1.2% compared with the control (Figure 10).The same treatment increased leaf dry matter yield by 63% (0.94 t ha^{-1}) and petiole dry matter (0.42 t ha^{-1}) by 207% compared with the control (Figure 11). Nitrogen encourages crop canopy growth as previously discussed by (Malnou *et al.*, 2006). The increase in f_{root} may be because the above ground yield proportionally was relatively substantially smaller than the irrigated treatment at the same rates of N. For the 300 N irrigated treatment there was 2.65 t ha^{-1} leaf DM and 3.22 t ha^{-1} petiole DM. As the leaves and petiole in the dry treatment are smaller it has a low sink strength for photoassimilates which is not significant enough to cause a decrease in f_{root}.

In irrigated plots 300 N decreased f_{root} by 8.3% compared with the control. The irrigated 300 N treatment had 21% greater canopy ground cover compared with 0 kg ha^{-1}. Irrigated 300 N increased leaf dry matter by 201% and petiole dry matter by 265% compared with the control. Irrigated 50 N increased leaf dry matter yield by a relatively low 26% and petiole dry matter yield by 31% compared with the control. This suggests why there was no significant effect of 50 N on root percentage in both water treatments as the biomass above ground did not have a large enough sink strength to cause a decrease in f_{root}. There was also a significant effect of the interaction between water and nitrogen on f_{root} for all treatments deemed significant. This suggests a priority of sink for photoassimilates when the plant has additional N fertiliser. As previously discussed, Gonzalez-Dugo *et al.* (2010) suggested that under irrigation water is refilled into the larger pores which lead to the mobilisation of N into the rooting zone, making it more available for uptake. This would lead to greater N being utilised by the plant therefore more assimilates going into the leaf and petiole which results in a decrease in f_{root}.

5.5 Considerations of crop management due to treatment

All nitrogen treatments under dry conditions reached 95% yield at a similar time, on average this was 177 DAP. The full growing period was 211 DAP therefore in terms of farm management there is potential to feed out the crop, sometime shortly after 177 DAP if feed is needed. It may not be worth leaving the plants in the ground for an additional 34 DAP although this treatment would never occur in the field as rainfall would be a major factor.

In terms of the irrigated treatment, the control and 50 N treatments reached 95% yield at a similar time. This happened at, 191 and 193 DAP, respectively. Considering how close it is to the full crop duration, it may not be worth feeding the crop out early. The 300 N treatment took 184 DAP to reach 95% yield where growth rate substantially decreased at the end of the crop duration as shown in Figure 5. Therefore there is an opportunity to feed out the crop approximately 9 DAP early when high rates of N are applied. However, it is unlikely to be economically viable to apply 300 kg N ha^{-1} as additional fertiliser and spreading costs would not cover the yield benefit. As well as this, there would be environmental concern for nitrate leaching as large amounts of N is being added to the soil therefore higher potential to be leached into surface and ground water.

5.6 Leaf Chlorophyll

There was 30% greater leaf chlorophyll concentration in the dry treatment compared with irrigated treatment (Figure 12). This result contradicts an experiment where sugar beet (*Beta vulgaris*) was treated with water stress and it was found that leaf chlorophyll levels were 38% lower than plants that were well watered. This inconsistence could be due to the fact the plants were only water stressed for 200 hrs; therefore, the leaves would have had a chance to expand to a reasonable size and chlorophyll to spread over a larger area. In rape seed increasing drought stress also decreased the chlorophyll concentration in the leaves, further contradicting this result (Naderikharaji *et al.*, 2008). A SPAD meter was used, similar to the Apogee chlorophyll meter in this experiment. A reason for this conflict is that the chlorophyll concentration may be higher in the dry treatment but overall in each leaf there is less chlorophyll just spread over 67% less area as shown by the fractional canopy ground cover data. As the area of the leaf is smaller,

chlorophyll is tightly spread therefore concentration is higher. In this experiment, the dry plants only had 10 mm of water applied with the addition of fertiliser. This meant over the crop duration, the leaves were constantly water stressed and expanded at a very slow rate which concentrated the chlorophyll into a small area. Another theory is that water stress causes greater thickness of the outer walls of the leaf cuticle and epidermis. This affects leaf greenness as measured by the chlorophyll meter (Wood *et al.*, 1993). The greater chlorophyll concentration in the leaves did not seem to benefit efficiency of plant growth as RUE was lower in the dry treatment compared with the irrigated treatment.

Nitrogen is a major component in chlorophyll. Greater nitrogen leads to greater production of chlorophyll in the chloroplasts (Andrews *et al.*, 2013). In the dry treatment, 300 N increased leaf chlorophyll by 10.3% compared with the control. Leaf N concentration correlates well with chlorophyll concentration (Wood *et al.*, 1993). In the irrigated treatment 300 N increased leaf chlorophyll by 13.8% compared with the control. The time of sampling had a significant effect on leaf chlorophyll concentration. This may be because of assimilates moving from older leaves to new emerging leaves over the crop duration therefore creating high variability in the data. Nitrogen did not increase RUE, for that reason chlorophyll concentration in the leaves had no bearing on efficiency of growth. Therefore, plant breeders, modellers and agronomists should focus on greater leaf area as it is the main component in reaching higher yield and leaf chlorophyll concentration is not a significant factor.

6 CONCLUSION

The main findings of the study were:

- The main factor limiting yield in fodder beet was water availability. This was mainly due to much greater canopy ground cover under irrigated conditions leading to greater radiation interception for growth. Secondary to this, RUE was also a vital component of yield among the different water regimes. RUE was significantly greater under adequate water availability.
- Nitrogen was also a major factor in limiting fodder beet yield. However, differences were much smaller comparatively compared with water stress. Under both water treatments, 50 N and 300 N greatly increased canopy ground cover leading to greater radiation interception. There was no significant effect of N on RUE.
- There was no significant difference in yield between 50 N and 300 N in both water treatments. However, the 300 N irrigated reached 95% maximum yield 9 DAP or 102 ^{o}Cd before the 50 N treatment, which reflected the highest LGR for the 300 N treatment. This indicates that 300 N grew faster due to greater N supply, but the light intercepted after this point did not result in net photosynthesis. There was a significant difference between 50 and 300 N at 183 DAP. Therefore 50 N is the better option for a farmer to apply after considering fertiliser price and spreading cost. The benefit of 300 N is the potential to feed the crop out early.
- The fraction of total dry matter partitioned in the root was higher in both limiting water and nitrogen conditions which was beneficial towards higher DM yield. This may be due to lower sink strength from the above ground biomass therefore more energy is partitioned in the root.
- Leaf chlorophyll concentration was higher in water stressed plants, and under greater nitrogen supply. Leaf chlorophyll concentration did not seem to benefit plant yield, as RUE was lower in water stressed plants and unaffected by nitrogen.
- Therefore, plant breeders, modellers and agronomists should focus on greater leaf area as it is the main component in reaching higher yield. Adequate water and nitrogen supply should of the utmost importance for farmers to reach high yields.

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9 APPENDICES

Appendix 1: Application date, agrichemical applied, application rate and active ingredient that was applied from sowing to end of trial.

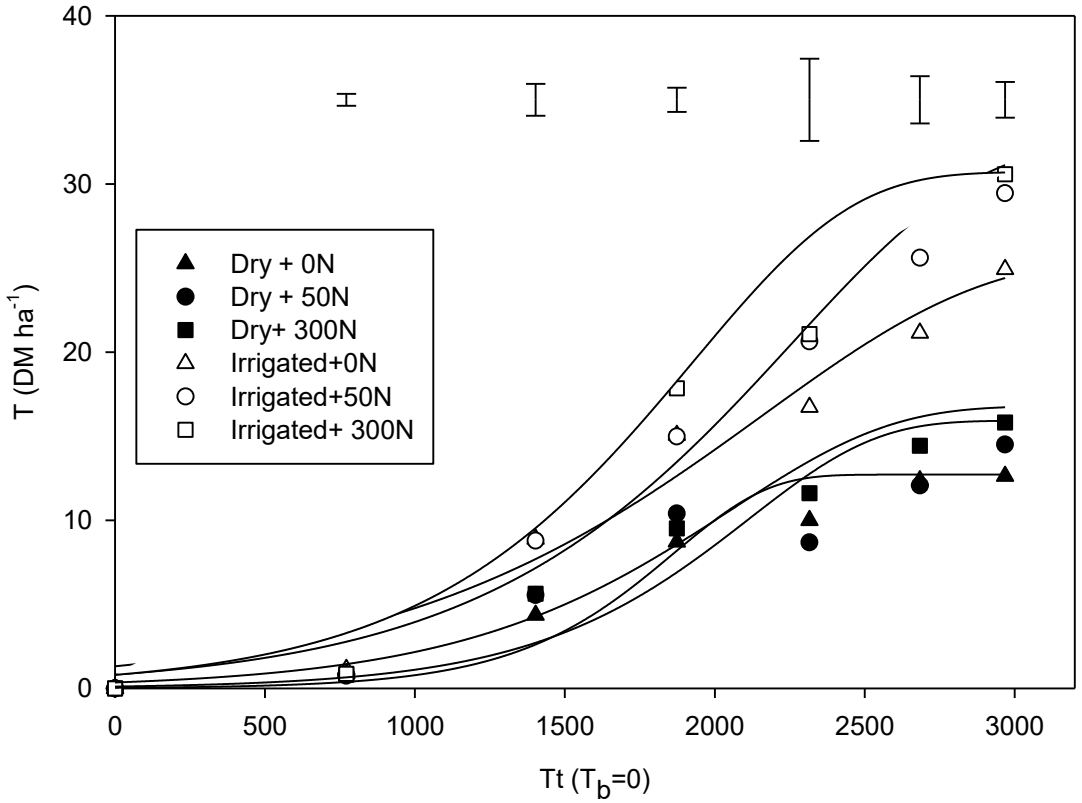
Date	Agrichemcial Applied	Application Rate	Active Ingredient
18-Oct-16	Clomazone (Magistar)	100 ml ha^{-1}	360 g L^{-1}
	Ethofumesate(Nortron)	2 L ha^{-1} in 200 L ha^{-1} water	500 g L^{-1}
27-Oct-16	Pirimiphos-methyl and permethrin (Attack)	200 ml ha^{-1} in 200 L ha^{-1} water	475 g L^{-1} and 25 g L^{-1} respectively
1-Nov-16	Pirimiphos-methyl and permethrin (Attack)	200 ml ha^{-1} in 200 L ha^{-1} water	475 g L^{-1} and 25 g L^{-1} respectively
21-Nov-16	Phenmedipham, desmedipham, ethofumesate, metamitron (Bentanal Quattro)	2 L ha-1	60 g L^{-1}, 60g L^{-1}, 60g L^{-1} and 200 g L^{-1} respectively
	Metamitron (Goltix)	1L ha^{-1} in 250L ha^{-1} water with Du-wett at 50 ml per 100 L	700 g L^{-1}
1-Dec-16	Pirimiphos-methyl and permethrin (Attack)	500 ml ha-1 in 200L water	475 g L^{-1} and 25 g L^{-1} respectively
7-Dec-16	Metamitron (Goltix)	1L ha^{-1}	700 g L^{-1}
	Phenmedipham and desmedipham (Bentanal Forte)	800 ml ha^{-1}	160 g L^{-1} for both
	Ethofumesate (Nortron)	600 ml ha^{-1} in 250 L ha^{-1} water	500 g L^{-1}
15-Dec-16	Lambda-cyhalothrin and oxirane, methyl polymer with oxirane,monobutyl ether (Karate Zeon)	40 ml ha^{-1}	250 g L^{-1} and 13.2 g L^{-1} respectively
	Pirimiphos-methyl and permethrin (Attack)	500 ml ha^{-1} in 200L water	475 g L^{-1} and 25 g L^{-1} respectively
20-Dec-16	Copper oxychloride	300 g in 100 L water	800 g kg^{-1} copper oxychloride in wettable powder form
29-Dec-16	Lambda-cyhalothrin and oxirane, methyl polymer with oxirane,monobutyl ether (Karate Zeon)	40 ml ha^{-1}	250 g L^{-1} and 13.2 g L^{-1} respectively
	Copper oxychloride	300 g in 100 L water	800 g kg^{-1} copper oxychloride in wettable powder form
10-Jan-17	Lambda-cyhalothrin and oxirane, methyl polymer with oxirane,monobutyl ether (Karate Zeon)	500 ml ha^{-1} in 200L water	250 g L^{-1} and 13.2 g L^{-1} respectively
2-Feb-17	Copper oxychloride (AgPro Copper oxychloride 800WP)	300 g in 100 L water	800 g kg^{-1} copper oxychloride in wettable powder form
8-Feb-17	Cyroconazole and trifloxystrobin (Escolta)	350 ml ha^{-1} in 200 L ha^{-1} water	160 g L^{-1} and 375 g L^{-1}
28-Apr-17	Cyroconazole and trifloxystrobin (Escolta)	350 ml ha^{-1} in 200 L ha^{-1} water	160 g L^{-1} and 375 g L^{-1}

Appendix 2: Irrigation application dates, plots applied and amount applied for the experimental site at Lincoln, Canterbury, New Zealand.

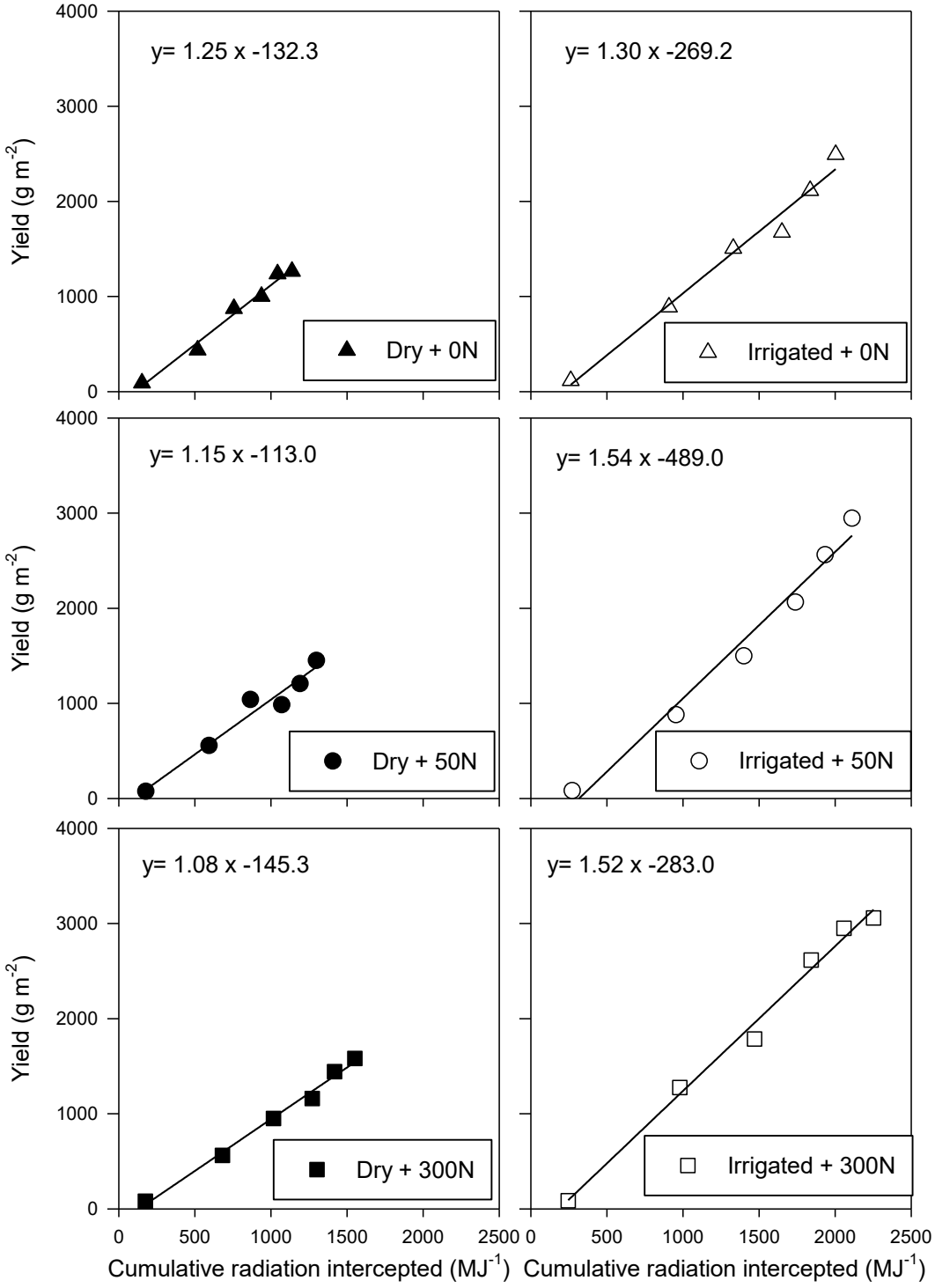
Date	Plots water is applied	Amount (mm)
23-Nov	All irrigated	30
30-Nov	All irrigated	30
7-Dec	All irrigated	25
14-Dec	All irrigated	0
21-Dec	All irrigated	25.2
29-Dec	All irrigated	30
4-Jan	All irrigated	40
11-Jan	All irrigated	32.9
18-Jan	All irrigated	25.4
25-Jan	All irrigated	31.3
1-Feb	300 N	40
8-Feb	All irrigated	33
15-Feb	All irrigated	35
22-Feb	All irrigated	29
1-Mar	300 N	32.6
8-Mar	All irrigated	34
15-Mar	All irrigated	0
22-Mar	All irrigated	50.1
29-Mar	All irrigated	0
5-Apr	All irrigated	0
12-Apr	All irrigated	30.9
27-Apr	All irrigated	18.9

Appendix 3: Image of marked leaves of one plant in plot 410 (Dry, 0 kg ha^{-1}), for chlorophyll concentration measurement, taken on 8th May 2017 at experimental site at Lincoln, Canterbury, New Zealand.

Appendix 4: Image of the operation of Apogee C-100 leaf chlorophyll meter, taken 23rd May 2017 at experimental site at Lincoln, New Zealand, Canterbury.



Appendix 5: Total dry matter (t ha^{-1}) measured from 27th October 2016 to 17th May 2017 against thermal-time from crop emergence measured in ^{o}Cd for two water and three nitrogen treatments applied to fodder beet crops grown at Lincoln, Canterbury, New Zealand, 2016-2017. Whole graph.



Appendix 6: Total cumulative dry matter (DM) measured from 27th October 2017 to 17th May 2017 against cumulative radiation intercepted (MJ^{-1}) from crop emergence for two water and three nitrogen treatments water and nitrogen treatments applied to fodder beet crops grown at Lincoln, Canterbury, New Zealand, 2016-2017. A regression line was fitted to give radiation use efficiency as displayed by the equation. RUE values and x intercept are shown in Table 7. Graphs are displayed separately.

Appendix 7: Total, leaf, petiole, root and dead dry matter (t ha^{-1} DM) for two water and three nitrogen treatments applied to fodder beet crops grown from October 2016 to May 2017 at Lincoln, Canterbury, New Zealand.

Treatment	Total (t ha^{-1})	Leaf (t ha^{-1})	Petiole (t ha^{-1})	Root (t ha^{-1})	Dead (t ha^{-1})
Dry+0N	12.62	0.58	0.20	10.66	1.18
Dry+50N	14.50	0.57	0.28	12.31	1.33
Dry+300N	15.81	0.94	0.42	13.52	0.92
Average Dry	14.31	0.70	0.30	12.17	1.14
Irrigated+0N	24.92	1.32	1.22	20.49	1.89
Irrigated+50N	29.44	1.66	1.59	24.31	1.88
Irrigated+300N	30.58	2.65	3.22	22.59	2.12
Average Irrigated	28.31	1.88	2.01	22.46	1.97
Nitrogen P value	0.001	<0.001	<0.001	ns	ns
Water P value	<0.001	<0.001	<0.001	<0.001	<0.001
N*W P value	0.361	0.002	<0.001	ns	ns
Nitrogen LSD 5%	2.137	0.204	0.2149	2.651	0.2549
Water LSD 5%	1.745	0.1665	0.1755	2.164	0.2082
N*W LSD 5%	3.022	0.2884	0.304	3.749	0.3605

Appendix 8: Birds eye view of experimental site with labelled treatments at Lincoln, Canterbury, New Zealand, 2016-2017. Photo was taken on the 15th May 2017, two days prior to final harvest.